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NEPHELINIZED PARAGNEISSES IN THE BANCROFT AREA, ONTARIO

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ABSTRACT

Geological mapping in the Bancroft area has indicated that the nepheline-bearing rocks were developed in metamorphosed sediments of Grenville type. The visible granite-syenite complex adjacent to the nepheline rocks is younger and intrusive into those rocks. Some obvious paragneisses locally contain nepheline, and an increase or decrease in nepheline content may occur both along and across the strike of the gneisses. In fact, some rocks were traced from a typical calcareous mica or hornblende paragneiss facies into rock rich in nepheline and containing little calcite. It was also noted that the nepheline-bearing rocks are not everywhere closely associated with either granite or limestone; they actually occur scattered throughout a very heterogeneous series of metamorphosed sediments. There is no field evidence that reaction took place between a granitic or syenitic magma and limestone to yield a feldspathoidal magma; neither do the nepheline rocks present intrusive relations to the other rocks; nor are there segregations of lime-silicates in the immediate neighborhood, which might be expected if limestone syntexis in its commonly accepted form had occurred.

The proposed hypothesis is that the nepheline rocks are the result of a process of "nephelinization," in which certain impure calcareous sedimentary horizons were attacked and replaced by solutions from some unknown but probably granitic source, resulting in the deposition of nepheline and sodic plagioclase without the formation of an actual nepheline-syenite magma, which has been postulated by proponents of the syntexis theory. Most of the nepheline pegmatites also appear to be replacements, although their origin is more doubtful.

INTRODUCTION

This paper presents the results of nearly eight months of detailed field work in the Bancroft area of nepheline rocks, in 1941, when possible domestic sources of aluminum were being investigated. Because the rocks were being examined for an economic purpose, the extent and nature of the nepheline-rock bodies were ascertained far more precisely than ever before. Exact relationships have been determined which on earlier maps were, of necessity, generalized. The very nature of the work enforced close study of certain aspects which might normally have been neglected or inferred. Furthermore the use of diamond drills yielded informative data, and the hypothesis advanced herein may therefore be said to be built on three-dimensional, rather than on two-dimensional, knowledge.

A material part of the investigation was the preparation of numerous chemical analyses of both surface and depth samples. As it happened, expediency dictated partial analyses only, on a routine basis in most instances; but, notwithstanding the fact that few complete rock

analyses were made, a wealth of analytical data has been gathered.

Although the area examined in greatest detail is a relatively small part of the whole alkaline-rock district, nevertheless the work done therein and the examination of neighboring exposures suggest that the results are definitely applicable to the district as a whole. An exception is the Blue Mountain deposit, where very little work was carried out. However, in addition to the brief study by the authors in that locality, some information was obtained from engineers of the American Nepheline Corporation. Some discussion of the Blue Mountain deposit is therefore included in the appropriate places.

THE BANCROFT NEPHELINE-ROCK AREA

DEFINITION AND MAPPING

The village of Bancroft is situated some 75 miles north of Belleville, Ontario, in Faraday Township, Hastings County. The "Bancroft area" is defined for the purpose of this paper as that area lying immediately to the east of Bancroft and comprising lots 23–30 inclusive, in Concessions XIII and XIV of Dungannon Township, and parts of Hastings Road Lots 58, 59, 60, and 61 in Dungannon and Faraday townships.

F. Chayes[1] has discussed the importance of map scale in portraying the geology of this area; his map was prepared on a larger scale and is more detailed than earlier maps. The present geological map comprises a still smaller area on a still larger scale and thereby brings out still more detail. The information was originally compiled at a scale of 200 feet = 1 inch, used in plane-table surveying; unfortunately, reduction to the size presented here has resulted in considerable loss of detail. The original map, however, has already been published at a scale of 10 chains = 1 inch.[2]

The information obtained from the survey is presented here in three separate maps. These three are equivalent to the map already published, but, on account of the reduction in size, separation has been necessary. Figure 2 illustrates the topography, with various hills named for convenience of reference; Figure 3 shows the occurrences of rock outcrops; and Figure 4 indicates the contacts, determined and assumed. The delineation of the rock boundaries is considerably different from that offered by Chayes.[3]

From time to time it will be necessary to refer to rocks outside the Bancroft area as defined above, but the following sections will apply in the main to that area.

GEOLOGICAL SETTING

The Bancroft area forms only a small portion of a larger district, which comprises the two counties of Haliburton and Hastings. These counties, on account of their mineral occurrences and good exposures of early pre-Cambrian sediments and volcanics, have been studied in considerable detail. The general rock sequence for the district as a whole, including the Paleozoic limestones and other rocks on the southern edge of the area, is given in Table 1. This information was compiled from existing reports and from recent field work.

The rocks which constitute the group of paragneisses and crystalline limestone and dolomite are those commonly termed "Grenville." They are found as great bands in a terrain of predominantly

[1] "Alkaline and Carbonate Intrusives near Bancroft, Ontario," *Bull. Geol. Soc. Amer.*, Vol. LIII (1942), p. 468.

[2] James E. Thomson, "Mineral Occurrences in the North Hastings Area," *Ont. Dept. Mines, 52d Ann. Rept.*, Vol. LII, Part III (1943).

[3] Ftn. 1.

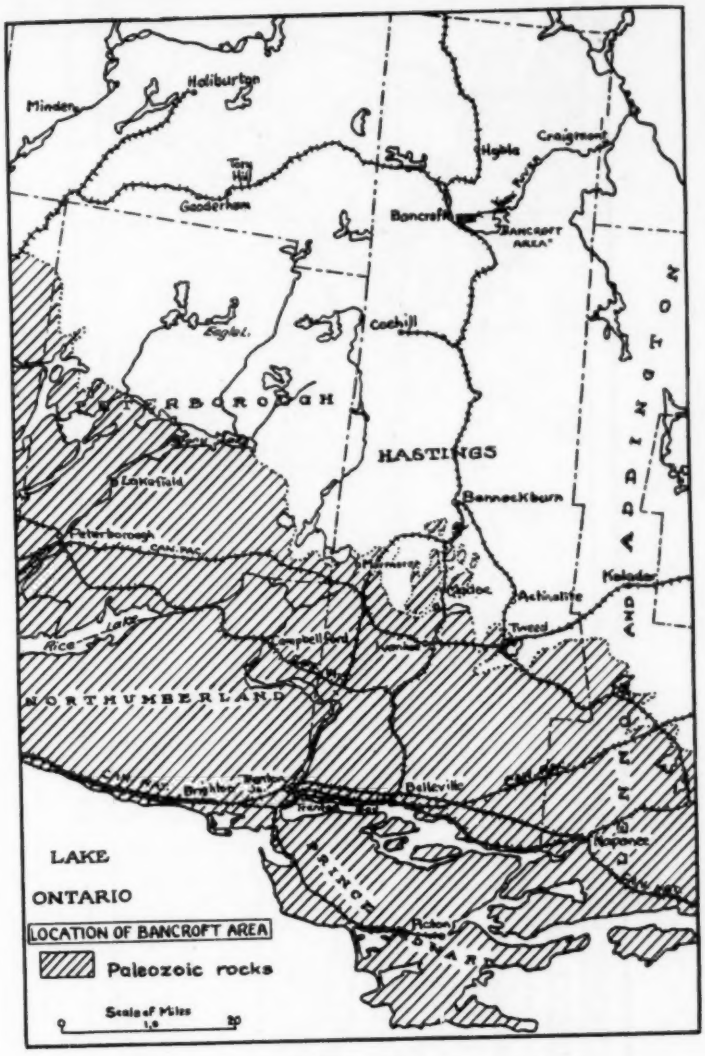

FIG. 1.—Index map showing location of Bancroft area

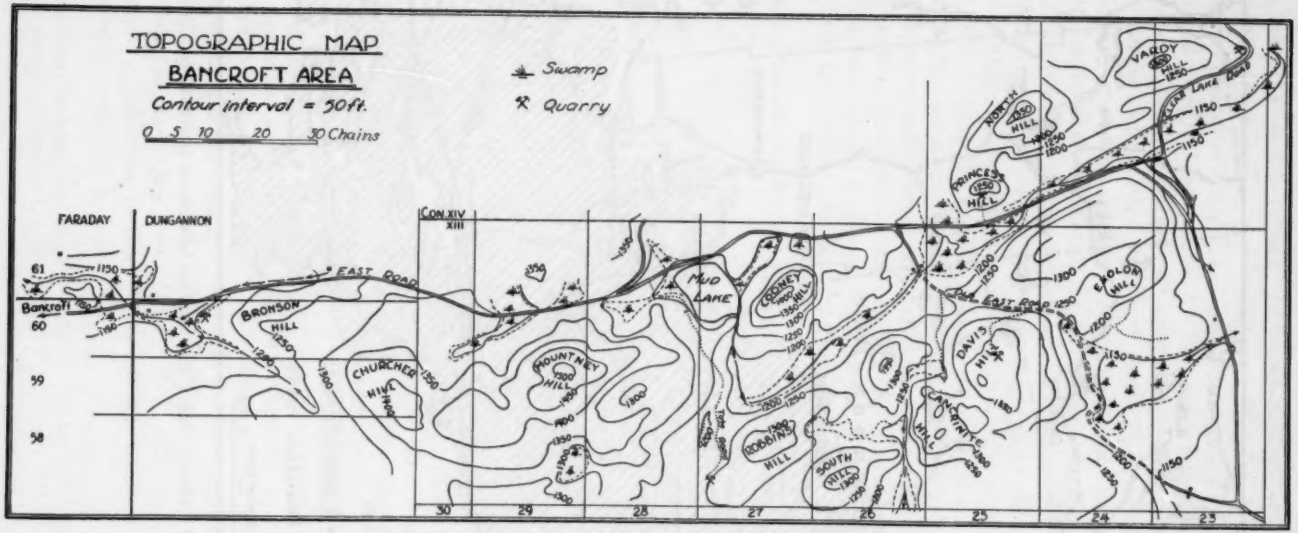

FIG. 2.—Topographic map of the Bancroft area

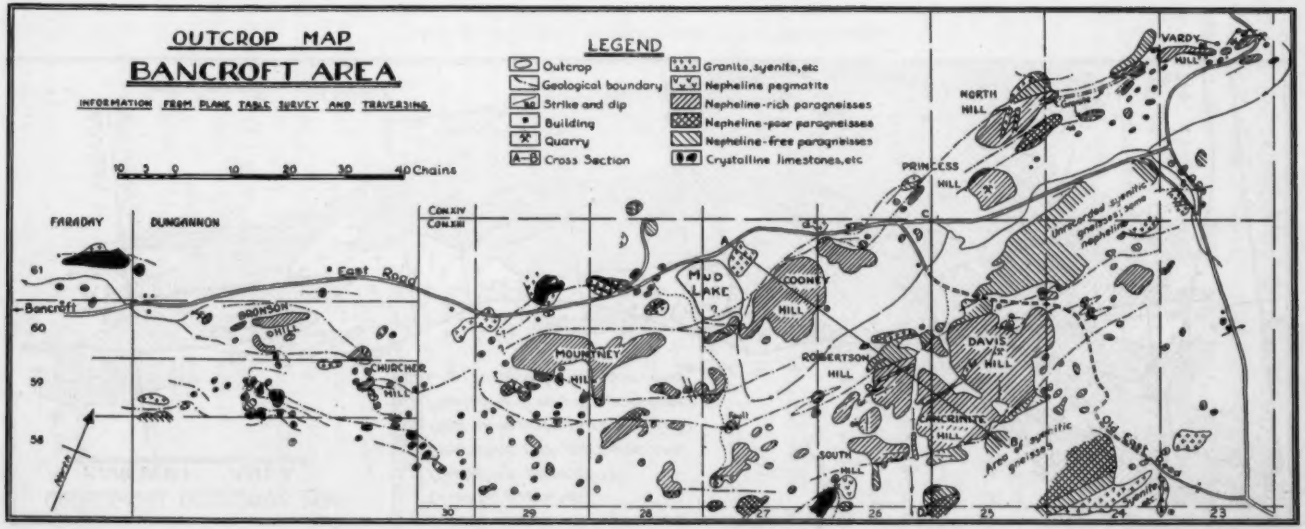

FIG. 3.—Outcrop map of the Bancroft area

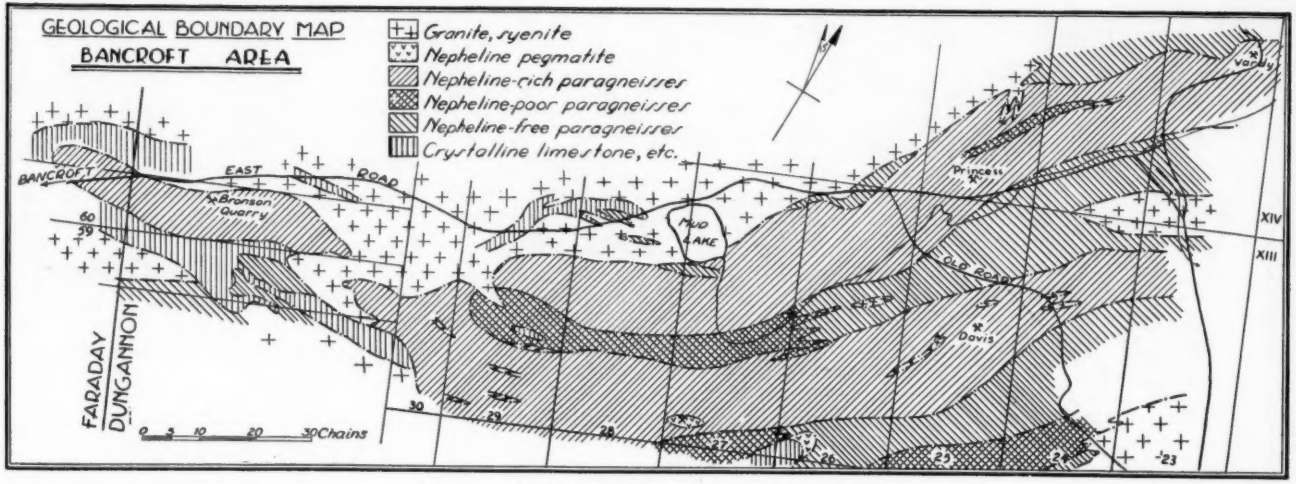

FIG. 4.—Geological boundary map of the Bancroft area

granitic gneisses and are intruded by several rock species, including granite. The nepheline-bearing gneisses, which are intimately associated with altered and recrystallized sediments of the Grenville type, were formed still later and were, in turn, invaded by syenite and granite. F. D. Adams and A. E. Barlow[4] recognized that the granite near Egan Chute, east of Bancroft, and the granite at Blue Mountain are younger than the nepheline rocks. M. L. Keith[5] came to the same conclusion for the Blue Mountain area and, indeed, believed that most of the granitic rocks of the nepheline-rock belt are younger. Recently Thomson[6] and J. Satterly[7] have recognized that the granitic rocks adjacent to the nepheline-bearing rocks are postnepheline, although Chayes[8] believes that the granites are either older or contemporary.

TABLE 1

GENERAL ROCK SEQUENCE, HALIBURTON-HASTINGS DISTRICT

Cenozoic	
Recent	Clay, sand, gravel, peat
Pleistocene	Clay, sand, gravel, boulders
Paleozoic	
Ordovician	Limestone, dolomitic limestone, sandy limestone, shale, arkose, quartzite*
Pre-Cambrian	Diabase
	Pink granite, syenite, and pegmatites
	Nepheline-bearing gneisses and pegmatites
	Granite, granite gneiss, hybrid gneisses
	Diorite, gabbro, anorthosite, peridotite
	Crystalline limestone, dolomite; amphibolite
	Conglomerate
	Micaceous and amphibolitic paragneisses, quartzite and graywacke
	Basic volcanics (hornblende schist, chlorite schist)*

* Ordovician rocks and Keewatin-type volcanics do not occur in the special area discussed in this paper.

The actual area of nepheline-bearing rocks is small, but they and the associated types occur in a more or less east-west, discontinuous belt, passing directly through Bancroft and possessing a total length of some hundred miles.

The bands and elongate bodies of the nepheline rocks conform to the strike of the associated rocks. Additional exploration may well bring to light more exposures and prove greater continuity to the belt.

The Blue Mountain deposit lies some distance south of the main belt, in Methuen Township near Peterborough.

PETROGRAPHY

LIME ROCKS

The lime rocks of the area vary from the relatively pure, coarsely crystalline limestone south of the Bronson Hill, through biotite-rich types and diopside-marbles, to an extremely impure amphibole-mica-calcite-feldspar rock, which not uncommonly carries nepheline or cancrinite. The minerals observed in the field and in thin-section studies are as follows:

calcite	dolomite
biotite	tremolite
albite	nepheline
oligoclase	garnet

[4] "The Geology of the Haliburton and Bancroft Areas, Province of Ontario," *Can. Dept. Mines, Mem. 6* (1910), p. 324.

[5] "The Petrography of the Alkaline Intrusive at Blue Mountain, Ontario," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 1795–1826.

[6] P. 9 of ftn. 2.

[7] "Mineral Occurrences in the Haliburton Area," *Ont. Dept. Mines, 52d Ann. Rept.*, Vol. LII, Part II (1943), p. 18.

[8] Pp. 497–98 of ftn. 1.

diopside	graphite
"hastingsite"	magnetite
muscovite	zircon
microcline	apatite
serpentine	spinel
cancrinite	

Besides the carbonates, the commonest minerals are the micas, diopside, the feldspars, and serpentine. Nepheline was observed in carbonate rocks in a few places, the most accessible exposure being in the railway cut in Bancroft village. There, steeply dipping gneisses include comparatively pure marbles and impure types, rich in silicate minerals and containing only small amounts of calcite and dolomite. Some of the rocks are similar to those earlier named "foyaite," "jacupirangite," etc.

Peculiar lime rocks are noticeable, such as the "flow marble"[9] below the sawmill on the York River in Bancroft, and the mylonitic facies on the road leading north near Mud Lake. The writers are in agreement with Chayes's findings that the flow marbles contain fragments of all rock *types* except those containing nepheline, but they disagree as to the age of the granite pebbles. The lime rocks of this type are cut by the visible granite. Some small rounded fragments of quartzite (or chert) were encountered, but no rock of that type was found in place within several miles of the locality.

In a thin section of lime rock from the railway cut the following relationships were observed: calcite, biotite, and microcline, in order of abundance and formation, are the chief minerals, magnetite and apatite being accessory. Patches of fibrous zeolite-like material, identical with the altered nepheline of other rocks, are partially replaced by albite. Biotite, associated with calcite, is embayed by the feldspars. The altered nepheline (?) is also associated with calcite. Microcline is the youngest mineral in the rock.

Similar relations have been observed in other sections, although nepheline or its alteration products are not present in every case.

MICACEOUS SCHISTS AND GNEISSES

Dark rocks rich in mica or, locally, in amphibole are abundant in the Bancroft area. They vary from relatively massive gneisses to strongly foliated schists; the massive varieties tend to be finer grained than the foliates. Many of them have been termed "shonkinite" by earlier workers.

Early in the study it was observed that certain bands of these paragneisses and schists contained nepheline. More careful examination brought to light the fact that basic rocks may actually change along the strike into gneisses, which carry a very appreciable amount of nepheline. This is particularly noticeable in the central band of basic rocks, cutting across Lots 23, 24, and 25 in Concession XIV and Lots 23, 24, 25, and 26 in Concession XIII; in Lots 27, 28, and 29 the rocks on strike with that band contain nepheline in increasing amounts. The change is gradual but is shown diagrammatically on the contact map on the east side of Lot 27, Concession XIII. The same gradation has been observed elsewhere not only along, but also across, the strike.

Many zones mapped as paragneiss,

[9] *Ibid.* In the present paper the question of large-scale intrusion of "carbonatite" is not treated in detail. The exposures, in the area, of "flow marble" are not considered so very different from similar exposures commonly found, where Grenville-type rocks exist (and where no alkaline rocks are found). The ability of calcite to "flow," to grout or seal fractured dikes or adjacent brittle sedimentary layers, and to be squeezed into certain structural openings, such as the nose of a fold, is well known.

adjacent to the granite and syenite, are granitic, obviously having suffered considerable attack by the intrusives. Indeed, in many places it is very difficult to place a contact between the basic paragneisses and the intrusives.

The minerals of the paragneisses and schists include the following:

"hastingsite"	scapolite
biotite	epidote
calcite	chlorite
albite	quartz
microcline	magnetite
perthite	garnet
pyroxene	sillimanite
muscovite	titanite

Garnet and sillimanite were not encountered in rocks of the Bancroft area, but they occur in schists not far to the south, in Lots 22 and 23, Concession X, Dungannon Township.

In the following sections some examples will be described. Since Adams and Barlow have presented very complete discussions of the mineral and textural relationships in most varieties of the rocks and since it was found that, in general, their conclusions were very acceptable, it does not appear necessary to reproduce them *in toto*. For further details the reader is therefore referred to the descriptions of Adams and Barlow.[10]

We are concerned chiefly with the foliates; the massive and finer-grained varieties are not abundant in the Bancroft area as defined and have not been observed to contain nepheline or its alteration products. Such rocks as the massive augite-hornblende-scapolite rock, occurring in the banded marble on the York River in Bancroft village, are referable to one of the groups of amphibolite set up by Adams and Barlow and probably represent impure limestones.

Dark micaceous rocks from the band along the East Road, Lot 24, Concession XIV, of Dungannon, contain green hornblende, "lepidomelane," sodic oligoclase, calcite, and apatite and titanite. The feldspars are somewhat altered to white mica, calcite, and epidote. The relation of calcite to the other minerals is rather uncertain; some appears to be original ("early"), other is secondary ("late"). Coarse calcite is associated with the ferromagnesian minerals and is apparently recrystallized original calcite. In one section it occurs in straight "laths," separated by the alternating development of mica foils.

A second gneiss from the same locality contains, in addition to the minerals mentioned above, microcline, some perthite, and scattered patches of fibrous material resembling highly altered nepheline in other rocks. Potash feldspars replace soda feldspars, and both embay hornblende.

Feldspathic gneiss from the Exolon Hill, Lot 24, Concession XIII, is composed of albite, biotite, microcline (perthite), and muscovite. The albite is clouded with small crystals of calcite, white mica, and epidote. The microcline is very fresh and is younger. The mica is partially converted to chlorite.

A light-colored gneiss from the Robertson Hill, Lot 26, Concession XIII, contains oligoclase, biotite, hornblende, iron oxides, and calcite. Veinlets of calcite cut the feldspar, mica, and altered hornblende (Fig. 5). Some large patches of almost fibrous calcite are continuous with the veinlets. Small crystals of fresh, secondary albite occur in altered areas; some of the alteration product appears to be fine-grained soda-zeolite (natrolite?), perhaps derived from nepheline.

FIELD RECOGNITION OF NEPHELINE

The pitted surface of the nepheline-bearing rocks is well known (Fig. 8). The

[10] Ftn. 4.

nepheline, being more soluble than feldspar, tends to be removed, leaving ridges and humps of feldspar. The surface of the attacked nepheline is generally smooth and of a bluish-gray color. However, in the Bancroft area and, indeed, in all the areas examined, it was observed that in some cases the nepheline was altered to a white or creamy material. At first glance the rocks with white-weathering nepheline appear to be merely highly feldspathic types.

FIG. 5.—Crenulated biotite (in paragneiss) grouted by calcite. Robertson Hill, Lot 26, Concession XIII, Dungannon Township. Crossed nicols, ×45.

The bluish alteration product, which is rather readily removed, may be due to a superficial formation of sodalite, whereas the white or cream coating may perhaps be cancrinitic. A tendency was noted for the white surface to be present on the underside of cliffs and overhangs or in areas where vegetation is abundant. The bluish coating is more common on exposed outcrops.

NEPHELINE-POOR GNEISSES

The rocks of this group include those outwardly similar to the dark foliates of the nepheline-free group of rocks but containing nepheline and also certain light-colored gneisses of feldspathic nature, containing a small amount of nepheline. It is not uncommon to find lenses of nepheline-rich material, $\frac{1}{4}$–2 inches in width, in the gneisses; the lenses do not present intrusive relations but, on the contrary, appear to grade, albeit rapidly, into the surrounding rock.

The minerals and their relations in the nepheline-poor gneisses are essentially the same as in the normal paragneisses, with the exception that nepheline and its alteration products are more common, hornblende and biotite are less frequently observed, and microcline is more abundant. Some examples may be described.

On the south side of the Davis Hill, Lot 25, Concession XIII, occurs a belt of light-colored, interbanded, nepheline-rich and nepheline-poor gneisses, adjacent to and including some of the nepheline-free foliates. A section across a zone of the light-colored rocks shows that nepheline predominates in certain bands, whereas microcline predominates in others. Definitely two ages of plagioclase feldspar are present; coarse-grained albite or sodic oligoclase is the older and is replaced by finer-grained albite. Both feldspars replace biotite along cleavages and also replace calcite. One grain of albite was observed with the twinning lamellae parallel to the cleavage of a calcite grain. In a second instance cleavage in a grain of calcite conforms with cleavage in adjacent albite, and twinning in the same calcite conforms with cleavage in a second albite grain. However, some calcite replaces the earlier feldspar along cleavages; therefore, there is more than one age of calcite. This behavior of calcite is rather prevalent.

Nepheline-poor rock from the Robert-

son Hill contains hornblende, albite, calcite, and microcline, with cancrinite and a zeolite, alteration products of nepheline; the microcline replaces albite. At what stage the nepheline was altered is not obvious. Coarse calcite, up to $\frac{3}{4}$ inch in size of grains, is present, with an unusual arcuate twinning traversing straight cleavage, possibly the result of gliding; it exhibits cataclastic effects along fractures. Cancrinite forms fan-shaped patches around altered nepheline in the albite.

Gneisses from Robbins Hill have high-calcite, biotite, and hornblende contents; but, in some, feldspar is absent; cancrinite is abundant; and some scapolite has been observed.

NEPHELINE-RICH GNEISSES

Albite and nepheline form the bulk of the nepheline-rich rocks, the former generally being predominant. Biotite, magnetite, and calcite are present in nearly every slide examined but are generally minor in amount. Throughout the area the feldspar is chiefly albite,[11] from Ab_{90} to Ab_{97} as determined by extinction angles in the zone normal to (010) and by other methods. Universal-stage study proves the albite is generally in the neighborhood of Ab_{95}. It has undergone little alteration, even in those rocks in which the nepheline is completely altered. In many cases the relations between albite and nepheline are somewhat doubtful, but in many others albite is definitely younger. Also in some sections there are at least two ages of plagioclase, the older containing a few per cent more of the anorthite molecule and commonly being fractured. Generally the nepheline appears to have formed between the periods of formation of the two plagioclases and occurs in anhedral to subhedral crystals, embayed by the younger albite. Nepheline, as well as the younger albite, may be strongly fractured in some examples, but the indications are that the prominent fracturing occurred before the nepheline formed.

In the rocks with most nepheline, calcite is least apparent; but it increases as nepheline decreases and as ferromagnesians increase. Some calcite occurs as replacement remnants, whereas other examples are obviously secondary or late, perhaps recrystallized. In some rocks calcite grains are found almost entirely as inclusions in albite or are interstitial, rarely occurring as remnants in nepheline. Blebs of calcite may be oriented, in optical continuity, parallel to crystallographic directions in albite.[12] Rims and fans of cancrinite are common between nepheline and calcite. Calcite veinlets cut nepheline-apatite-calcite rock on Robertson Hill and in many other localities.

One particular section from Davis Hill is composed of rounded crystals of albite, nepheline, and biotite, separated from each other by calcite. Cores of calcite are also seen in cancrinite, against nepheline. The texture is identical with that found in recrystallized limestones containing silicate minerals.

Biotite, of the deeply pleochroic "lepidomelane" type, is common but rarely exceeds 10–15 per cent and is generally much less than that. Magnetite is typically to be found in intimate association with biotite, as is calcite. Some

[11] Oligoclase and even andesine are found in some types, for example, the "craigmontite" and "dungannonite" of Adams and Barlow (pp. 312 and 322, respectively, of ftn. 4).

[12] Chayes (Pl. 3, Fig. 2, facing p. 466, of ftn. 1) shows, in the left-hand picture especially, what might be taken as an excellent example of "caries," the result of the replacement of calcite by feldspar. Chayes interprets this as calcite replacing feldspar.

magnetite has been observed in skeletal crystal aggregates, of which the interstices are filled with finely crystalline albite. Hornblende ("hastingsite") is present, but rarely in the nepheline-rich rocks.

Apatite and zircon are minor but widespread, and eucolite or a similar rare-earth mineral has been observed. Occasionally, small apatite-calcite-feldspar bodies are observed and are probably related to the fissure fillings of similar mineralogy that have been adequately described by Adams and Barlow and others.

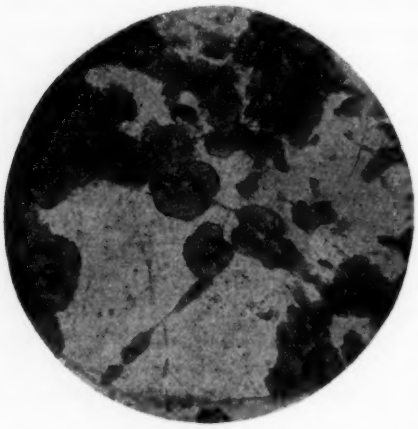

FIG. 6.—Zeolitic alteration of nepheline rock. Rosettes of secondary minerals growing along cleavages and cracks. Davis Hill. Crossed nicols, ×45.

Potash feldspar is also minor in quantity and is the latest-formed mineral, occurring interstitially to albite and nepheline and in some sections replacing those minerals. It is noticeably more abundant in certain bands, where it is frequently associated with the more intense alteration of the nepheline. It has been observed also that microcline is more abundant adjacent to the pink syenitic dikes that are so common.

The nepheline is generally very fresh; but, adjacent to joints, faults, or dikes, it may be completely altered to fine-grained fibrous mats of cancrinite, sodalite, gieseckite (?), calcite, and a mineral that is apparently a soda-zeolite of the natrolite group. The commonly mixed nature of the alteration products does not lend itself to an accurate determination of the component phases. Sodalite has been observed as pseudomorphs after nepheline, but it also occurs in veinlets and separate grains of apparently primary nature.

The alteration products of nepheline were studied rather carefully. Several sections show positively that the alteration increases toward dikes (albitite in particular) and openings along which solutions might have operated. The alteration generally proceeds by the formation of fibrous, radiate-structured spherulites along cleavages, fractures, and grain contacts (Fig. 6). In one instance the alteration of nepheline adjacent to a joint was observed to have resulted in cancrinite near the joint but in zeolitic products farther away.

On the northwest flank of Robertson Hill occurs a lens or band of corundum-albite-nepheline rock. Corundum occurs in crystals reaching 1 inch or more in length and is separated from nepheline by albite.

NEPHELINE PEGMATITES

Two typical pegmatitic bodies are those occurring in the south parts of Lots 26 and 27, Concession XIII. They are composed essentially of nepheline and albite, crystals of the former reaching as much as 3 feet in length. Other minerals recognized are biotite; magnetite; sodalite; cancrinite; green, violet, and mauve "grieseckite"; orthoclase; and microcline. The bodies of rock are not

dikelike in form but are irregular in outline.

Elsewhere in the area, patches of pegmatitic rock are abundant. On the west flank of Cancrinite Hill occurs a zone of striking yellow cancrinite and blue-to-purple sodalite, which is simply an alteration of the nepheline gneisses. On Princess Hill, Lot 25, Concession XIV, there is an irregular length of pegmatitic albite, microcline, and sodalite, at one time worked for ornamental stone. The occurrence is characterized by numerous vugs. The feldspars tend to be euhedral, in a groundmass of streaked sodalite. No intrusive relations were observed; on the contrary, the body seems to be a replacement.

Throughout the area large crystals of nepheline may be encountered in the fine- to medium-grained nepheline gneisses. An outstanding example was noted on a large angular piece of float in the valley to the south of Davis Hill. A shear zone crosses the foliation of the nepheline gneiss roughly at right angles. Two crystals of nepheline, about 8 inches in longest dimension and euhedral in form, have been developed across the crack and also across several albite-rich bands. Remnants of the albite-rich bands remain in the nepheline crystals and show distortion. This seems to be a clear case of recrystallization of the nepheline, with concomitant replacement of the host-rock.

Another feature of such examples is the common association of large magnetite crystals with the coarsely crystallized nepheline. In some of the coarser gneisses, vugs were observed, lined with euhedral magnetite crystals reaching $\frac{1}{2}$ inch in diameter. One large body of magnetite is known; and several dikelike bodies, the largest about 15 inches wide, were encountered. A paragenetical relation between recrystallized ("regenerated") nepheline and late magnetite is indicated.

Another point worthy of observation is the abundance throughout the region as a whole of pegmatitic zones, streaks, and bodies containing coarse calcite with the silicates. The well-known occurrences of calcite fillings or replacements in joints in nepheline rock, lined with coarse nepheline, albite, mica, and apatite, are examples. Several pegmatites locally have extremely coarse-grained calcite matrices, and others contain lenses of more or less pure calcite. There is, then, an obvious conclusion, that the pegmatites were closely connected with the formation of calcite in large amounts.

ALBITITE DIKES

Under this heading are classed those bodies of rock, large and small, that are composed almost entirely of albite and that are apparently cross-cutting.

Study of the weathered surface of many exposures of the nepheline rocks yields an interesting fact: the rock is *not* invariably an intimate granular mixture of albite and nepheline; instead, those minerals tend to be segregated into bands. A "stringer" of albite, perhaps only $\frac{1}{8}$ inch wide, may be perfectly continuous for several feet, composed of adjoining crystals of albite that at first glance may appear to be evenly dispersed throughout the nepheline (Fig. 7). Wider bands are continuous over still greater distances. It was observed in the field that the contacts of some of the albite "dikes" with nepheline gneisses are gradational. Some crystals or crystal aggregates of albite are actually shared by the gneiss and the "dike," and some attenuated streaks of albite in the nepheline rock may be seen to pass uninterruptedly into the coarser albite of the

"dike" (Figs. 7 and 8). This immediately suggests that the albite might have been formed, at least in part, by simple silication of nepheline, which spread laterally from joints and fractures—a process that

FIG. 7.—Albite stringers in nepheline-rich gneiss. Lot 27, Concession XIII, Dungannon Township.

appears likely by virtue of the fact that the visible granitic rocks are postnepheline in age.

The albitite rocks are most conspicuous, if not actually most abundant, in the Bronson Hill exposures. They occur throughout the area, however, and are evidently most abundant adjacent to granitic or syenitic contacts.

Under the microscope, Bronson Hill albitite presents the following relationships: albitite of high purity comprises well over 95 per cent of the rock; microcline is perhaps the next most abundant mineral. Calcite, magnetite, biotite, apatite, zircon, white micas, and sodalite are present. Microcline is younger than the bulk of the albitite and is associated with finer-grained albitite and, quite frequently, with skeletal magnetite aggregates. Calcite occurs as rounded replacement remnants. The presence of sodalite suggests a genetic connection with the nepheline rocks; it occurs as small subhedral grains interstitial to the albite, with no indication that it represents original nepheline. However, small and irregular patches of material very similar to the altered nepheline of other rocks are present.

Chayes[13] has suggested that some albite-rich pegmatites, dikes, and veinlets represent "either a syenitic residue which has somehow escaped desilication, or late acid pegmatite which has been 'albitized' by the addition of solid alkalies and alumina"; or that the albitite has been formed by reaction of foyaitic liquid and solid syenite. The writers conclude from examination that the veinlets in the Vardy Quarry (mentioned by Chayes) and elsewhere are the result of siliceous mineralizers acting on nepheline, which is the opposite effect to that postulated by Chayes. However, he does mention the possibility that some "veinlets of syenite . . . . may be the product

FIG. 8.—Relations between nepheline-rich gneiss, albitite (with nepheline), and nepheline pegmatite. Bronson Hill.

of reaction between a nepheline-rich rock and very small quantities of highly silicic liquid."[14] This would seem to be a more correct interpretation.

[13] *Ibid.*, p. 488. [14] *Ibid.*, p. 496.

GRANITE, SYENITE, ETC.

The obviously intrusive rocks, then, are apparently limited to the granite, syenite, and related types. These latter include quartz syenite, biotite and hornblende syenite, granite and syenite pegmatite, and feldspar-rich dikes, which are pink and appear in decided contrast to the white "albitite dikes." Granite is commonly gradational into syenitic border facies; in other places the granite is gradational into paragneisses, and it is entirely arbitrary with which group of rocks the granitization product is to be mapped. A good deal of rock included with the granite is gneissic and contains obvious remnants of paragneiss (sometimes containing nepheline, as in the east end, Hastings Road, Lot 60, and in the north half of Lot 28, Concession XIII, just west of Mud Lake).

In several localities quartz-bearing granite is in immediate or very close contact with limestone or nepheline-bearing rocks. Granite with abundant quartz occurs in the east half of Hastings Road, Lot 59; to the north of that, nearer the East Road; and just west of Mud Lake. The intrusive tongues north of Princess Quarry and much of the rock along the East Road in Lot 23, Concessions XIII and XIV, contain quartz. Quartz pegmatite is found on the flank of Robertson Hill, in nepheline-poor and nepheline-free gneisses. Quartz-aplite cuts nepheline rock on Davis Hill. Only a few of the feldspar-rich dikes and sills are of mappable dimensions, and some of those shown are approximated.

Much of the syenitic phase is blotchy, with inclusions of altered paragneisses. Under the microscope the rock is seen to be composed essentially of microcline and perthites; some microcline and albite are younger than the perthite.

The following minerals have been recognized in the granite and related rocks:

perthites	apatite
microcline	titanite
orthoclase	zircon
albite	pyrite
quartz	white mica
biotite	epidote
hornblende	chlorite
augite	serpentine
magnetite	

The presence of the iron-rich "lepidomelane" and of "hastingsite" in the intrusives has previously been used as a criterion of consanguinity with the paragneisses and nepheline rocks which contain the same minerals.

No calcite has been observed in normal granite, whereas it is common in the syenites. Yet the granite can be seen to grade into syenite where overburden does not mask the relations.

STRUCTURE

The delineation of a recognizable structure, which includes the nepheline-bearing rocks as important units, has been as helpful as any other phase of the study in pointing to the origin of the nepheline rocks.

The rocks of the area are everywhere more or less gneissic, the nepheline rocks lying in definite bands intercalated between gneisses, whose sedimentary origin is at once apparent (Figs. 9, 11, and 12). The strike of the rocks is prevailingly northeast; dips are mainly southward and vary from almost vertical to as low as 10°.

Even the granite, especially adjacent to the gneisses, has a pronounced foliation that may be primary ("flow") structure or inherited through granitization. Many intrusive bodies show concordant relations, as, for example, the main north and south contacts of the granite and syenite with the paragneisses and the

lens-shaped smaller bodies. Elsewhere contacts are obviously of intrusive, discordant character. The bodies of paragneisses west and north of Mud Lake appear to be large inclusions or remnants caught up in the granite.

Drag folds are common, recognizable chiefly in the micaceous parasediments and the crystalline limestones but also found in nepheline rocks (Fig. 10). The limestone in east Lot 61, Faraday Township, is dragged in such fashion as to suggest an anticline to the south, plunging to the west. However, drag folds located elsewhere indicate a syncline plunging to the east and, therefore, that drag folding may indicate only local effects in the readily folded limestones.

FIG. 9.—Well-banded paragneisses, south of Davis Hill, Lot 25, Concession XIII, Dungannon Township.

There are two main bands of nepheline-bearing rocks which unite in Lots 29 and 30, Concession XIII, and continue as one band to the west (see Fig. 4). In east Lot 59, Dungannon Township, as nearly as can be ascertained from surface exposures, granite has isolated the westward extension. Lying between the two bands, from the east end of the mapped area to their junction, is a belt of rocks, which in the eastern section is composed chiefly of nepheline-free paragneisses with a few narrow nepheline-bearing bands. This facies apparently grades into gneisses carrying nepheline, which increases in quantity westward along the strike. A similar gradation is to be found to the south of the southern band of nepheline-rich rocks in Lots 26 and 27, Concession XIII. Still farther south occurs a band of paragneisses with minor nepheline (Lots 23, 24, 25, and 26, Concession XIII). A comparable zone is present north of the East Road in Lots 26 and 27, Concession XIV, but is not shown on the map. Small bodies of nepheline-poor rock occur here and there throughout the nepheline-rich and nepheline-free rocks.

The explanation offered here of this distribution is that the nepheline gneisses and other paragneisses are parts of an overturned syncline plunging to the northeast. The succession of the gneisses in the area covered by the map is roughly as shown in the accompanying tabulation.

Inner belt.....	Some limestone, calcareous schists and paragneisses, occasional nepheline
	Nepheline-poor paragneisses
Middle belt.....	Nepheline-rich paragneisses
Outer belt.....	Nepheline-free and nepheline-poor paragneisses
	Crystalline limestone, etc.

The limestone in center Lot 29, Concession XIII, is explained as a synclinal remnant, remaining because of the local topography. The limestone along Concession XIII in Lots 26 and 27 is believed to be on the nose of an anticline to the south, the outline of that nose being indicated by the concordant nepheline pegmatite in the same area. Limestone is suggested as a continuous band around the west end of the syncline toward Ban-

croft. The long, dissected body of limestone north of the East Road in Lots 28 and 29, Concession XIII, is a remnant of the same band. The two bodies were separated by the granite, which has invaded the nepheline-rock belt, and apparently some limestone has flowed, as suggested by Chayes, but not after emplacement of that granite. Impure limestones interbedded with more or less calcareous paragneisses were encountered in a drill hole on the west side of Cooney Hill, between nepheline rock and granite.

The straight gorge of the creek below Mud Lake may indicate a fault. If so, it would aid in explaining the appearance of a lens of nepheline-poor and nepheline-free gneisses (mapped as "nepheline-free") just below the lake. A fault may also be present between Davis and Robertson Hills. Minor faulting is present throughout the area (Figs. 11 and 12).

The sinuous outline of the main belt, especially north of the East Road in Concession XIII, is due in large part to topography (Fig. 14). However, there has certainly been folding and faulting later than that which formed the major structure.

The strikes of the nepheline gneisses, on Davis, Cancrinite, Cooney, Princess, and North hills, trace out subsidiary drag folds on the arms of the major fold (Fig. 15). Owing to the overturned nature of the fold, the axial dips of the drags in the two arms are similar.

ANALYTICAL DATA

Adams and Barlow[15] presented several analyses of what they considered type nepheline rocks. On the basis of the C.I.P.W. classification, they set up several new species of nepheline rocks. Among the old and new types recognized were essexite, laurdalite, nepheline syenite (vulturose), monmouthite, miaskite, syenite (kallerudose), craigmonitite, raglanite, and dungannonite. It is contended that many additional and different analyses could have been obtained, because, in those finely foliated gneisses, contiguous bands have different compositions both chemically and mineralogically. Adams and Barlow themselves remarked on the strikingly rapid variation of the rocks, which is difficult to explain if the nepheline rocks are considered to be intrusive.

FIG. 10.—Drag-folding in paragneisses on south side of Cancrinite Hill, Lot 25, Concession XIII.

During the course of the present investigation many analyses were made; although most of them were only partial, there is sufficient variety that still other rangs and subrangs of the C.I.P.W. classification could be set up. However, field evidence negates the value of applying those recasting methods to the nepheline rocks. Our analyses indicate that the amounts of the various oxides in the rocks cover a wide range. For instance, silica varies from 35 to 60 per cent in rocks of the area; alumina varies from 17 to 34 per cent. Samples from all parts of the area have been analyzed;

[15] Ftn. 4.

study of the results has shown that, in the Bancroft area, the total of the R_2O_3 constituents is commonly around 30 per cent (see Tables 3 and 5). If Al_2O_3 comprises 25 per cent, Fe_2O_3 and TiO_2 (and MnO, P_2O_5, ZrO_2, etc.) comprise about 5 per cent; if Al_2O_3 is 20 per cent, the other oxides are about 10 per cent; and if Al_2O_3 is 30 per cent, the other oxides are low, 2 or 3 per cent.

The rough constancy of the sum-R_2O_3, that is, the indicated reciprocal relation between Al_2O_3 and Fe_2O_3, and the similar relation between CaO and alkalis (as comprising the larger part of the undetermined portion in the analyses) are believed to have some bearing on the origin of the nepheline rocks.

The analyses have also shown that certain zones within the main nepheline bands contain more nepheline than others. These zones have been outlined as drag folds and appear as S-shaped bodies. Their disposition agrees with that

FIG. 11.—Fault in mixed nepheline-poor and nepheline-free paragneisses, Lot 27, Concession XIII.

FIG. 12.—Details of downthrow side of fault shown in Figure 11. A 1-foot syenite pegmatite seals the fault.

FIG. 13.—Crumpling of paragneisses (some with nepheline) and limestone. Egan Chute, York River.

FIG. 14.—View looking westward from Davis Hill. Cooney Hill in right center distance, Mountney Hill in left distance.

of the apparent drag folds on the limbs of what has been assumed to be the major syncline. It then appears that the distribution of nepheline-rich zones is determined by the structure, and therefore it is logical to conclude that the nepheline was formed after the major folding. The general fracturing in the earlier feldspar of the gneisses and the lack of that fracturing in most cases in the nepheline agree with this conclusion.

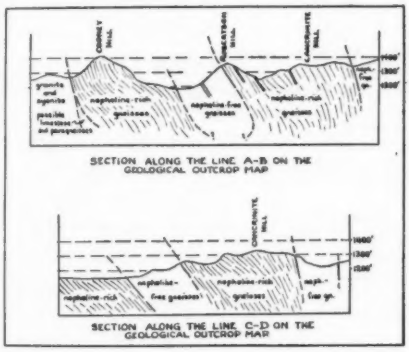

FIG. 15.—Cross-sections as indicated in Figure 3, showing secondary folding on limbs of the major overturned fold.

Analytical results also suggest that, in some places, rocks at the surface are richer in alumina than those occurring at depth. This probably indicates that calcite has been removed at the surface by weathering, yielding a relative increase in the other oxides. Some analyses are given in Table 2.

A typical drill-core log is given in Table 4, showing the variation recognized. In Table 5 are presented the analytical data on the samples represented by the log.

OTHER AREAS OF NEPHELINE ROCKS

YORK RIVER AREA

A relatively small amount of work was done by the writers in the York River area (the band of paragneisses, crystalline limestones, and nepheline-bearing gneisses along the east side of the York River, north of the East Road, some 6 miles east of Bancroft). Some important information was, however, derived from the study.

TABLE 2

ANALYSES OF NEPHELINE ROCKS

Oxide	I*	II	III	IV	V	VI
SiO_2.....	47.2	48.2	41.8	49.7	47.4	54.6
TiO_2.....	0.1	n.d.†	0.3	0.1	0.2	0.2
Al_2O_3.....	28.1	26.3	29.5	22.4	27.4	21.6
Fe_2O_3.....	3.7	4.1	5.2	6.8	3.1	1.9
MnO.....	0.02	n.d.	0.02	n.d.	n.d.	n.d.
CaO.....	1.7	2.1	5.1	1.3	1.8	3.6
MgO.....	0.5	n.d.	1.3	n.d.	n.d.	n.d
L.O.I.....	1.8	2.8	1.3	1.7	1.6	3.6
R_2O_3.....	31.9	30.4	35.0	29.3	30.7	23.7

* I—Surface sample, 11 feet width, Mountney Hill, Lot 29, Concession XIII, Dungannon Township. Analyst, W. K. Gummer.
II—Surface sample, 360 feet width, Princess Hill, Lot 25, Concession XIV, Dungannon Township. Analyst, E. M. Weaver.
III—Surface sample, 13 feet width, north ½, Lot 8, Concession XIV, Dungannon Township. Analyst, W. K. Gummer.
IV—Core sample, 71.5 feet length, Davis Hill. Analyst, E. M. Weaver.
V—Core sample, 13.5 feet length, Bronson Hill, Lot 60, Hastings Road. Lots, Dungannon Township. Analyst, E. M. Weaver.
VI—Core sample, 13.5 feet length, Bronson Hill. Analyst, E. M. Weaver. (Contains albitite dikes and altered [cancrinitic] nepheline.)

† n.d. = not determined.

TABLE 3

AVERAGE R_2O_3 FIGURES, BANCROFT AREA

Sample Description	Percentage R_2O_3
35 core samples, 1330.8 feet, nepheline-bearing rocks.....	29.4
66 core samples, 2029.0 feet, nepheline-bearing rocks.....	29.5
8 core samples, nepheline-free gneisses, syenite, etc.....	27.0

The nepheline rocks are generally quite different from those of the Bancroft area. They appear to lie in more definite and less contorted bands, and the parasedimentary rocks associated with them are perhaps somewhat more abundant.

Most of the rocks contain far more hornblende and biotite, less feldspar, and generally less nepheline; accessory minerals include red garnet, corundum, zircon, and eucolite, which are rare or lacking in Bancroft area rocks but which in York River rocks may locally become important constituents. Microcline is but rarely to be found, but scapolite is more common than in the Bancroft area.

TABLE 4

SAMPLE DRILL-CORE LOG

Hole 7 — Bearing N.72° W. ast. — Length, 258 feet
Exolon Hill — Lot 24 Concession XIII Dungannon Township — Angle 45°.)

Footage	Description	Sample	Width
0.0– 7.0	Casing		
7.0– 45.0	Medium- to fine-grained nepheline rock; small quantity of dark minerals, mainly hornblende; 0.5 feet biotite-calcite band at 9.5 feet; strong "gieseckite" alteration over last 10 feet		
	7.0–25.0, as above	40	18.0
	25.0–45.0, as above	41	20.0
45.0– 71.7	Coarser nepheline rock, with larger amount of biotite and hornblende; alteration to "gieseckite" common; apparently higher feldspar		
	45.0–71.7, as above	42	26 7
71.7–100.0	Finer-grained nepheline rock with lower ferromagnesian content; considerable pink and green alteration; feldspar content appreciable; 0.8 foot calcite-sodalite at 82.0		
	71.7–100.0, as above	43	28.3
100.0–105.0	Much biotite; hornblende and feldspar; small amount of nepheline		
	100.0–105.0, as above	44	5.0
105.0–111.5	Nepheline rock similar to 71.7–100.0		
	105.0–111.5, as above	45	6.5
111.5–141.0	Very patchy nepheline rock, locally rich in dark minerals; much "gieseckite" and natrolite alteration; pink syenite dikes 121–23, and 129–32; several small syenitic sections		
	111.5–141.5, as above	46	29.5
141.0–258.0	Syenitic rocks, little or no nepheline; calcite-biotite-cancrinite, 214.1–214.9; sampled		
	141.0–151.0, as above	47	10.0

TABLE 5

ANALYSES OF SAMPLES 40–47 INCLUSIVE

SAMPLE	PERCENTAGE							
	L.O.I.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	Total Determined	R_2O_3
40	3.7	48.5	0.28	24.3	5.2	5.9	87.9	29.8
41	3.3	46.7	0.30	26.1	5.4	2.7	84.5	31.5
42	6.4	44.9	0.32	19.2	9.0	7.6	87.4	28.5
43	3.6	49.3	0.28	24.0	5.3	3.3	85.8	29.6
44	2.4	46.9	1.54	17.3	11.5	7.5	87.1	30.3
45	4.3	50.6	0.26	25.5	4.5	2.6	87.8	30.3
46	2.7	51.8	0.92	17.1	8.9	3.7	85.1	26.9
47	1.4	54.3	0.50	19.9	7.8	3.0	86.9	28.2

Green hornblende may form as much as 80 per cent of some of these rocks; in others biotite of the deeply pleochroic type takes its place in part. Garnet occurs both as separate crystals and as rims (reaction?) around hornblende crystals or crystal clusters. No rocks were observed to which Chayes's term "migmatite" could be applied. He states that "the garnet-hornblende-nepheline rocks near Egan Chute . . . . are produced by injections of nepheline pegmatites into garnet-amphibolite."[16] The mixture is actually very intimate, the result of a soaking rather than an injection. It was in this area that F. F. Osborne was led to believe that replacement had played a part in the development of the nepheline rocks.[17]

The contrast between the mineralogy of the York River rocks and the Bancroft area rocks is further discussed at a later point. In the York River area the sum-R_2O_3 again tends to be similar in various rock types, although it is considerably higher than 30 per cent in the iron-rich varieties. Alumina determinations vary from 8 to 31 per cent, and iron oxide averages around 10 per cent. Alkalis (6–12 per cent) and silica (30–45 per cent) are lower than in the Bancroft rocks; lime is higher, reaching 19 per cent in certain rocks.

It has already been stated that Adams and Barlow considered the granite occurring west of Egan Chute to be younger than the nepheline-rocks.[18] In further support of that contention is the existence of quartz-bearing pegmatites that cut the nepheline gneisses. For example, a few hundred feet north of the East Road, a quartz-feldspar pegmatite cuts across interbedded nepheline gneiss and crystalline limestone. Where the dike traverses the nepheline rock, the amount of quartz is restricted and is confined to the center of the dike.

In the first small quarry encountered on the road paralleling the York River, nepheline pegmatite underlies limestone and has apparently replaced a portion of that rock. Near by the limestone is much coarsened in grain size and contains abundant red garnet, black spinel, and white cancrinite. Farther north, nepheline pegmatite apparently cuts across the crest of a drag fold in nepheline gneiss. Other pegmatites observed have rather irregular and indefinite contacts.

THE TORY HILL–GOODERHAM AREA

The rocks of this area have points in common with rocks of both the Bancroft and the York River areas. All are gneissic and are associated with similar parasedimentary rocks. Locally, limestone contains pebbles and possibly represents the limestone-conglomerates occurring some miles to the south and southeast.

On Lot 34, Concession IV, Glamorgan Township, four features are marked: (1) Typical biotite schist and hornblende gneiss locally contain nepheline; Satterly[19] has recently corroborated this. (2) Nepheline pegmatite has been traced half a mile or more, following the drag-folded configuration of the metamorphosed sediments. (3) The contact between the coarse pegmatite and the crystalline limestone, exposed in a small quarry, is entirely gradational. Away from the pegmatite, silicates, including nepheline and albite, are present in the limestone; and in the pegmatite, decreasing in size and abundance away

[16] Chayes, p. 486 of ftn. 1.

[17] "The Nepheline-Gneiss Complex near Egan Chute, Dungannon Township, etc.," *Amer. Jour. Sci.*, Vol. XX (5th ser., 1930), p. 33.

[18] Cf. ftn. 4.

[19] P. 17 of ftn. 7.

from the limestone, are remnants of that rock. Replacement is the only satisfactory explanation to account for the bulk, at least, of the pegmatite. (4) One 8-inch albite-nepheline band in "nepheline-amphibolite" (gneiss) appears to be intrusive; the nepheline is concentrated along the medial line of the dike.

The type "monmouthite" area (Lots 9, 10, and 11, Concessions VII and VIII, Monmouth Township) includes rocks in which the nepheline content varies from 10 to 95 per cent of the whole. The nepheline rock also contains green hornblende, biotite, albite, calcite, graphite, cancrinite, and zeolite-like alteration products of nepheline. The northern contact in one place is seemingly gradational into crystalline limestone containing much hornblende, as well as graphite, tourmaline, titanite, and chondrodite. Some limestone south of the Gooderham–Tory Hill road, in the same area, contains scattered crystals of nepheline.

THE BLUE MOUNTAIN AREA

The Blue Mountain area has been described by Keith,[20] who carried out a great deal of petrographic study and concluded that the nepheline rock is intrusive. He also decided that the granitic rocks are younger than the "litchfieldite," supporting his field evidence with age determinations by helium ratio.

The evidence gathered in other areas prompted some examination of the Blue Mountain exposures. Keith has stated that there is little evidence of deformation of the intrusive; however, it has been observed that both vague streaks and more prominent schlieren in the nepheline rock are strongly contorted. Indeed, the general delineation of the boundaries of the alkaline rock suggests tight folding. The Blue Mountain rock is, however, much more massive than rocks of the other areas.

In the rocks examined toward the southern end of the body in the present quarry, corundum is present but was not observed in actual contact with nepheline. It is found only in certain horizons, in irregular patches of albite with spinel (hercynite?) in the nepheline rock reaching several feet in length. Drill cores were studied and indicated that a correlation of horizons was possible, which is tantamount to saying that a pronounced stratification or foliation exists.

Chemically, the Blue Mountain rocks show less variation and are richer in silica and lower in lime than are the Bancroft rocks. Alumina and alkalis are about the same, although the ratio K_2O:Na_2O is greater in Blue Mountain rocks, in which potash feldspar is an important constituent.

THEORETICAL CONSIDERATIONS

GENERAL DISCUSSION

The study of alkaline rocks, not only of the area under consideration but also of many other areas, has given rise to a voluminous literature. Space does not permit a thorough review of that literature, nor is it deemed requisite.

Among the major theories of the formation of alkaline rocks in general, the following may be listed: (1) desilication of granitic magma by limestone,[21,22] (2) fractional crystallization,[23] (3) volatile

[20] Ftn. 5.

[21] R. A. Daly, *Igneous Rocks and the Depths of the Earth* (New York: McGraw-Hill Book Co., Inc., 1933).

[22] S. J. Shand, "Limestone and the Origin of Feldspathoidal Rocks," *Geol. Mag.*, Vol. LXVII (1930), pp. 415–26.

[23] N. L. Bowen, *The Evolution of the Igneous Rocks* (Princeton, N.J.: Princeton University Press, 1928).

transfer and concentration,[24,25] and (4) combinations and variations of the first three.

The alkaline rocks of the Haliburton-Bancroft region were early considered related to the granites and the limestones. Adams and Barlow[26] stated that the nepheline syenite and its associated alkali syenites represent marginal differentiation of the granite. On the basis of their study they distinguished four rock groups, believed to be consanguineous differentiates of one highly alkaline and aluminous magma.

Later work has consistently pointed to the connection betweeen the limestone and the nepheline rocks, although just as consistently assuming at least the bulk of the latter to be intrusive.

Osborne [27] concluded that some rocks in the York River area are replacements rather than intrusives. Keith[28] believed the Blue Mountain nepheline rock to be intrusive, but he realized that the granite there and elsewhere in the nepheline-rock zones is younger. H. W. Fairbairn[29] examined a specimen of the "litchfieldite" and concluded that it possesses a fabric that is probably due to magmatic flow and crystallizing pressure.

Recently Chayes has supported the limestone-syntexis hypothesis as developed by Daly, Shand, and others. He reports the development of syenite as a marginal facies of the granite, and shonkinitic hybrids as a result of the "intimate mixing of amphibolite with syenitic liquid."[30] He rejects Keith's age determination of the granitic rocks, chiefly, it appears, on the ground that the helium-ratio determinations used were of doubtful accuracy, although Keith presented field evidence that the "syenodiorite" is younger than the "litchfieldite." As a result of his decision that the granites of the Bancroft area are not postnepheline in age, Chayes has some difficulty in reconciling the syntexis hypothesis with the abundance of "late acid pegmatites" and concludes that they exist "in spite of assimilation."[31]

The present evidence requires a further change in viewpoint. We now know that the nepheline rocks do not occur entirely in limestone or between limestone and granitic rocks; on the contrary, they occur in bands in a very heterogeneous series of altered sedimentary rocks and were invaded by the visible granite. At least some of the rocks hitherto termed "shonkinite" are shown to be nothing more than facies of the metamorphosed sediments; others appear to be hybrids between granite and sediments. Certainly, some syenite has been developed at the borders of the granite, but it may be found against several types of paragneiss, including those with nepheline.

The following features may be reviewed:

[24] C. H. Smyth, Jr., "The Genesis of Alkaline Rocks," *Proc. Amer. Phil. Soc.*, Vol. LXVI (1937), pp. 535–80.

[25] J. L. Gillson, "On the Origin of Alkaline Rocks," *Jour. Geol.*, Vol. XXXVI (1928), pp. 471–74.

[26] P. 228 of ftn. 4.

[27] Ftn. 17.

[28] Ftn. 5.

[29] "Petrofabric Relations of Nepheline and Albite in Litchfieldite from Blue Mountain, Ontario," *Amer. Min.*, Vol. XXVI (1941), pp. 316–20. As a matter of fact, almost any rock, even unconsolidated material, may exhibit a fabric, particularly those rocks affected by metamorphism in any of its manifestations. Evidence of a fabric in Bancroft rock was obtained from thin-section study; for instance, the albite grains in one slide yielded a large number of near-centered optic-axis figures. The albite and biotite show greater tendency toward preferred orientation than does nepheline.

[30] P. 495 of ftn. 1.

[31] *Ibid.*, p. 504.

1. The nepheline rocks are generally banded in character.
2. The nepheline rocks are conformable in attitude to the surrounding gneisses and schists, and they exhibit similar structures.
3. There is a gradation from nepheline-free normal paragneisses and schists, through nepheline-poor rocks into nepheline-rich rocks.
4. Calcite is present in widely varying amounts in all the rocks except the typical quartz-bearing granite; in the paragneisses and nepheline rocks, it is least in those richest in nepheline and increases with increasing biotite.
5. In general, the silicates appear to have been formed at the expense of calcite; there is also considerable younger calcite.
6. Nepheline is commonly unfractured, and zones of high-grade (alumina-rich) nepheline rock appear to have been localized by previously developed structural features.
7. There is no field evidence at erosion levels of the production of nepheline-syenite magma through reaction between solid limestone and granite magma.
8. The visible examples of intrusive, cross-cutting nepheline rocks are very rare and are limited to certain pegmatitic bodies.
9. The granite and syenite are definitely younger and intrusive into the nepheline rocks; reaction between them and limestone appears to have been limited to the production of some more basic facies of the intrusives and of pyroxenitic and amphibolitic contact rocks of the limestones.

Proponents of the limestone-syntexis hypothesis, which, as applied in the Bancroft area, proposes the development of nepheline syenite and more specialized *magmas* through the assimilation of solid limestone by granite magma, must account for those features. There are some obvious difficulties.

THE NEPHELINIZATION HYPOTHESIS

The theory is here advanced that the nepheline rocks are the result of the replacement of certain horizons of the sedimentary series by materials emanating from a source as yet unknown, at some time after the major structural features had been formed. This process, which may be termed ***nephelinization***, apparently took place in large part through a reciprocal reaction involving soda and lime. That is indicated, of course, by the presence of some rocks relatively rich in calcite and poor in nepheline and albite and of others poor in calcite and rich in the alkaline silicates and by the presence in some rocks of two (or more) ages of plagioclase feldspar, the younger being richer in soda.

The term "nephelinization" is here used to specify the end-result and does not imply that nepheline was, or was not, added as such.

This hypothesis was first advanced in abstract form.[32] Satterly[33] and Thomson[34] have reached much the same conclusions from somewhat less detailed study. Replacement will explain all the major difficulties, including the continuity of the nepheline-bearing horizons on a large scale, the structure, and the variation of mineral constituents.

If limestone syntexis, with the usual concept of the production of actual nepheline-syenite magma, occurred at all, it must have done so at depth, beyond the zone of observation; this process would have been followed by upward movement of the newly formed feldspathoidal liquid, intrusion into various sediments, solidification, and, finally, intrusion of normal granitic magma and its satellitic dikes.

In contrast, the nephelinization hypothesis calls for the addition of material in liquid form (or volatile, or both) to solid strata *in situ*, without the actual

[32] W. K. Gummer and S. V. Burr, "The Nephelinized Paragneisses of the Bancroft Region, Ontario," *Science*, Vol. XCVII, No. 2517 (1943), pp. 286–87.

[33] P. 17 of ftn. 7.

[34] P. 14 of ftn. 2.

formation of a separate feldspathoidal magma or magmas.[53]

The concept of "granitization," whereby existing rocks become modified, through the action of mineralizers from granite magma, to a state in which they contain the minerals of a granite and in extreme cases resemble a granite not only mineralogically but also texturally, enjoys a favorable reception. The process of "albitization" is also fairly widely accepted. The process of "nephelinization," the term here indicating what is formed rather than what is added, is pictured as operating in the same general manner; but in this case some feature—whether physical or chemical—of either the mineralizers or the sediments, led to the formation of the undersilicated compound, nepheline, along with albite. Later action by the younger granite[36] produced still more albite in the nepheline rocks, probably by the process known as "silication" in the sense that silica was added to the rocks.

CHARACTER OF THE NEPHELINIZATION PROCESS

Nature of the rocks prior to nephelinization.—Conceivably, several distinct types of rock might undergo attack by igneous emanations to yield undersilicated compounds rich in soda and alumina. The addition of soda and silica to alumina-rich minerals, the addition of soda and alumina to feldspathic materials, the addition of soda to aluminum silicates—such reactions may be guessed at, but their substantiation is another matter. Equations might be written to illustrate the various conceivable reactions. The following are presented as possible rock types capable of undergoing alteration to nepheline-bearing rocks:

1. *Saline deposits.*—None are known in this or other areas of Grenville-type rocks.
2. *Arkoses.*—None are known in this area.
3. *Lateritic deposits.*—None are known, but the suggestion is an intriguing one, since an ancient weathering product of lateritic nature would be rich in both alumina and iron.
4. *Shales or slates, or such rocks as sillimanite schists.*—Quartz-sillimanite schist is known in the region, but in minor quantity. Although occurring not far from nepheline rocks, i shows no signs of the development of nepheline.
5. *Impure lime rocks.*—These contain alumina, silica, and iron in addition to calcium carbonate.

In the Bancroft region there is evidence of the existence of only types 4 and 5, and the rocks of type 4 are quantitatively unimportant; nor is there any indication in nepheline rocks that they were derived from aluminum-silicate rocks. On the other hand, mica (amphibole)-feldspar-calcite rocks, undoubtedly of sedimentary origin, are common, and many contain nepheline or minerals which are logically classed as alteration products of nepheline. It is therefore indicated that the "nephelinized" rocks were originally impure calcareous sediments. How much of the mineralogy of the paragneisses is the result of prenepheline metamorphism is not known.

The possibility that the nepheline rocks were formed from the purer varieties of the crystalline limestones has naturally been considered but has been discarded, (1) since nepheline is far more abundant in the impure calcareous rocks,

[35] T. T. Quirke has suggested a rather similar origin ("pneumatolytic replacement") for the nepheline rocks of the French River area, Ontario (personal communication).

[36] At this point we can mention the hitherto all-important areal association of the granite with the nepheline rocks. The apparently zonal relationships between the two rock types have been considered by Chayes (p. 498 of ftn. 1) and others as unlikely if the granite is the younger rock. However, the emplacement of the granite was probably in large part controlled by the same structural features that localized nephelinization.

(2) because in those rocks it is possible to recognize several degrees of nephelinization, and (3) because, although relatively pure limestones are to be found containing nepheline and other obviously introduced minerals, the source of the nepheline is generally indicated to be connected with a pegmatitic body. The rocks that are here considered as representing impure calcareous sediments may contain a trace, a medium amount, or a great deal of nepheline; whereas relatively pure limestones apparently contain only a little or none at all.

There is another aspect that merits consideration, namely, the existence in syenite and in nepheline-free and nepheline-bearing paragneisses of "lepidomelane" and "hastingsite" of identical nature. Previously, that association has been interpreted as a criterion of consanguinity of the granite, syenite, "shonkinite," "foyaite," and so forth. Under the present hypothesis, that distribution of the ferromagnesian minerals of rather unusual characteristics is logically explained as the result of contamination of the granite, by inclusions of the paragneisses whose composition was such that "lepidomelane" and "hastingsite" were formed (or which already contained those minerals).

Composition of nephelinizing solutions.—The field and laboratory work have produced three chief items of interest, which must be considered in the discussion of the mode of origin of the nepheline rocks: (1) The nepheline rocks were formed *in situ* by some process of replacement, and whether or not we can at present suggest the chemistry and mechanics of the process forming them, that fact remains. (2) The aluminosilicates of many of the nepheline rocks replace calcite. (3) There is a reciprocal relation between Al and Fe, such that, as Al_2O_3 increases, Fe_2O_3 decreases and, as Al_2O_3 decreases, Fe_2O_3 increases. In the rocks containing appreciable quantities of nepheline the sum-R_2O_3 approximates 30 per cent; in lower-grade rocks the sum-R_2O_3 is less, but the ratio Fe/Al increases rapidly with decreasing Al_2O_3. Paralleling this relation is that between lime and alkalis. Although there may be danger of overemphasizing the relation between Fe and Al, it does appear to be more than fortuitous.

Irrespective of the exact source and accepting the impure calcareous nature of the rocks prior to their alteration, it is obvious that soda in some form has been added. Generally soda-rich derivatives of granitic and syenitic magmas (and it is from such magmas that a soda-rich derivative is to be expected) are presumed to be, at the same time, silica-rich, as expressed empirically by "Na_2SiO_3." The presence of much silica immediately renders unlikely the ultimate formation of feldspathoids, unless that silica is first combined with some other substance ("desilication").

The petrographic evidence is strong for the development of nepheline and albite as replacements of calcite; it is impossible to escape the conclusion that calcite has played some prominent role in the formation of the nepheline rocks. If the nephelinizing solutions were actually albitizing solutions which underwent desilication through reaction with $CaCO_3$, perhaps along the lines suggested by the following equation:

$$NaAlS_3iO_8 + 2CaCO_3 = NaAlSiO_4 + 2CaSiO_3 + 2CO_2,$$

then the reaction was outwardly similar to Daly's postulate.[37] The difficulty now,

[37] Note that other reactions may be written in this fashion, such as $CaCO_3 + 4NaAlSi_3O_8 = 2NaAlSi_3O_8 \cdot CaAl_2Si_2O_8 + Na_2SiO_3 + SiO_2 + CO_2$, which is a *silicating* reaction. There is, of course, no

as always, is to explain the whereabouts of the lime silicate which was formed—in other words, there is no evidence of such a reaction. It is not easy to claim that reaction products have been removed, since lime tends to form rather insoluble compounds with silica; but either it was removed or it did not react in that fashion. If it did not, the nepheline-producing solutions were of one of two types: (1) they contained nepheline or the ingredients requisite for the formation of nepheline, in appropriate proportions, or (2) they were deficient in silica, and a desilication reaction was unnecessary, the silica of the sediments taking part in the reactions with the incoming soda and alumina. In connection with the first alternative, it has been suggested, as a way out of the difficulties posed here and elsewhere by the apparent nonexistence of lime-silicate reaction products, that desilication occurred at depth and that the magma thus formed then migrated upward. Even if that were so, the fact remains that that magma did not invade the sediments and solidify as an entity in the fashion of normal magmas; it replaced the rocks in what must have been a slow and dynamically tranquil manner. If this desilication occurred, the products of the reaction were not exposed, nor were they encountered in a considerable diamond-drilling program.

Were the solutions essentially carriers of soda and alumina, i.e., deficient in silica, the process would be more simply a reciprocal reaction between the solutions and the rocks into which they permeated, whereby the rocks gained in soda and alumina and lost lime (and iron?).

The abundance of calcite of late generation, especially in pegmatitic zones, suggests that CaO and CO_2 remained in close association, if not actually as $CaCO_3$, which might be possible in solutions low in silica. If that was the case, lime silicates never did form as a result of a desilication reaction, and the calcite which was replaced by feldspar and feldspathoid later reappeared simply as calcite.[38]

It is known that limestones, otherwise fairly pure, have albite and nepheline locally developed. This is especially (but not invariably) true adjacent to pegmatites, and, since the pegmatites may not be strictly similar to the gneisses in mode of origin, perhaps this is not conclusive; nevertheless, in such occurrences it is shown that soda, alumina, and silica have combined to replace calcite.

The rocks of the York River and Bancroft areas appear to be of the same general horizon of sedimentary material. Therefore, at one time they were presumably of the same general nature, i.e., impure lime rocks but varying from place to place in degree of impurity. If the rocks were originally similar, the York River gneisses may now resemble most closely the original composition of the sediments. That suggests that alumina and alkalis have been added and that lime and iron have been subtracted. This seems to have been the case in the Bancroft area in particular, where the iron content of the gneisses is lower than in York River rocks but where there are local concentrations of magnetite. Some rocks near Tory Hill are rich in nepheline but also contain a high percentage of magnetite; nevertheless it is the general

evidence that this ever occurred or that it could occur, but the first replacement of calcite appears to have been oligoclase.

[38] This raises the question of the nature of solutions that would dissolve calcite but precipitate nepheline, also acid-soluble to some degree. Perhaps the solution of $CaCO_3$ was aided by retention of CO_2 in the system under more or less neutral conditions.

case that alumina and iron bear a rough inverse relation to each other.

The iron content of the nepheline rocks has been the subject of much previous discussion; its origin remains in some doubt but can be limited to two possibilities: (1) it existed in the original sediments and in some places was merely recrystallized, in others was removed to be redeposited elsewhere, or (2) it was brought in with the nephelinizing solutions and deposited during this process. It is evident from the foregoing discussions that the first is considered the more reasonable conclusion. Since iron does form volatile compounds and transportation by or as volatiles has been accepted in certain instances, there is a possibility that it has in this case been associated with volatiles at some stage. The difficulty now is to reconcile the replacement of $CaCO_3$ by alumina-rich silicates and the inverse relation between Al and Fe.[39] It does not seem that there would be such a relation had the iron been introduced. The relation, however, may be taken as evidence that alumina has been introduced, and possibly some kind of balance was attained during the process of nephelinization between the silicate radical and the R_2O_3 substances. It may even be that that balance determined the ultimate degree of nephelinization.

Now, at any rate, the Al_2O_3 and Fe_2O_3 exist, for the most part, in separate and specifically unrelated minerals. The bulk of the iron oxides occurs as magnetite, and, furthermore, much of the magnetite appears to have been developed late in the nephelinization process.

However, a control of some kind on the process by the original composition of the sediments is strongly suggested. This statement implies that nephelinization occurred in rocks of rather definite constitution and that chemical factors, in addition to physical factors, played a part.

The possible importance of volatiles in the concentration and transportation of alumina and alkalis has been stressed by both C. H. Smyth,[40] and Gillson.[41] Daly and, later, Foye,[42] who elaborated on the theory, had suggested that the volatiles resultant from a desilication reaction might concentrate alumina and alkalis in the upper regions of the magma chamber. Smyth and Gillson, however, conceived the volatiles to be juvenile rather than the result of reaction, for instance, between granite and limestone.

The rocks containing nepheline are, then, pictured as originally ferriferous, siliceous, lime-bearing sediments. It is more logical to assume the addition of soda and alumina rather than the addition of soda alone, although some alumina undoubtedly existed in the rocks at the start. To what extent silica was added is not certain, but it must have been introduced to some degree. In purer varieties of limestones adjacent to pegmatites, silica has certainly been introduced; in fact, the minerals albite and nepheline appear to have been introduced there as such. The role that

[39] A good deal of speculation in an attempt to explain the relation Fe: Al could be recorded, but it is most definitely speculation. For instance, since it appears that Fe must be linked with Al or with the carbonates that were replaced by Al (etc.), is it possible that at one time the Fe existed as FeO in carbonate of a sideritic nature, that it was for some reason unstable at temperatures and pressures attained during the replacement process ($FeCO_3$ dissociates at a much lower temperature than does calcite), and that it was in part oxidized to yield magnetite and in part dissolved, to re-form again later as magnetite?

[40] "The Origin of Alkaline Rocks," *Jour. Geol.*, Vol. XXXVI (1927), p. 40.

[41] P. 473 of ftn. 25.

[42] W. J. Foye, "Nepheline Syenites of Haliburton County, Ontario," *Amer. Jour. Sci.*, Vol. XL (4th ser., 1915), p. 424.

volatiles have played is also uncertain, but the mineralogy and the textures testify to their activity; volatiles presumably would be far more mobile than liquids alone and would also be more capable of traversing minute rock openings.

Source of the nephelinizing solutions.—If the nepheline rocks are the result of replacement, somewhere there must have been a source of supply for the agents that carried out that replacement. The following possible sources may be suggested:

1. Gabbro, diorite (York River, Madoc area, etc.). There is no evidence forthcoming of any genetic connection between the gabbro or diorite of the Bancroft area and the nepheline rocks. However, Adams and Barlow indicated a nepheline gabbro on their map, and W. G. Miller[43] described a corundum-plagioclase-hornblende rock, which he believed was related to the nepheline rocks.
2. Harbingers of the exposed, younger granite, the altered rocks later being invaded by further advance of the parent-magma. Such relations are not unknown.[44]
3. Some granitic or syenitic body that perhaps never manifested itself by intrusion in the zone of observation or, if it did, has since been masked by the younger granite.

The evidence pointing to the origin of the solutions is scanty, but we have this much information: that the introduced materials contained soda and alumina and apparently not much silica. The possibilities as to the source of soda- and alumina-rich solutions are several, but it is most logical to expect that the immediate source of supply was a salic body; and if that body were itself a derivative by fractional crystallization from a more basic magma, then it would be equally logical to expect a concentration of volatiles in that salic derivative. The one-time activity of volatiles in the formation of the nepheline rocks has been attested by mineralogy and texture in several instances.

If the reported occurrences of basic rock containing nepheline and corundum are truly igneous and intrusive, it would be of interest to consider the possibilities of a genetic relation between the soda-alumina emanations and those basic rocks. Indeed, unless those rocks are proved otherwise than intrusive, they must be included in the broad picture. It is perhaps interesting to note further that anorthosites, containing in the neighborhood of 30 per cent Al_2O_3, occur in the general region and are related to definite gabbroic intrusives.

However, with the present information, it seems preferable to suggest only that the soda and alumina were immediately derived from a granitic or syenitic source, a source which itself is of uncertain origin and nature.

FURTHER COMPARISON OF YORK RIVER, BANCROFT, AND BLUE MOUNTAIN AREAS

Although field relations have indicated that the nepheline rocks were in all probability developed from a persistent horizon of sedimentary material, the mineralogical differences between the rocks of the areas are noticeable. Those differences are considered to be due, in the main, to the following five factors:

1. Original variations in the sediments
2. Arrest of the process of nephelinization at various stages
3. Differences in physicochemical conditions attained, resulting in contrasted mineral assemblages
4. Amount of deformation, i.e., availability of structural openings
5. Degree of modification of the nepheline rocks by the younger granite

[43] "Notes on the Corundum-bearing Rocks of Eastern Ontario," *Amer. Geol.*, Vol. XXIV (1899), pp. 276–82.

[44] H. C. Horwood, "Granitization in the Cross Lake Area, Manitoba," *Trans. Roy. Soc. Canada*, Vol. XXX, Sec. IV (3d ser., 1936), pp. 99–117.

The Bancroft rocks are richer in nepheline, on the whole, than are the York River rocks. It has been suggested that (making allowances for original compositional differences) the York River rocks have undergone less nephelinization than have the Bancroft rocks. Following this hypothesis, it might be conjectured that the Blue Mountain rocks, which least resemble sediments, are furthest advanced in the nephelinization process. It is interesting to note that the York River rocks show least contortion, the Bancroft rocks considerably more, and that the structure that is visible in Blue Mountain rocks is a highly contorted one.

The fifth factor must be considered, since the action of the younger granite may have resulted in further mineralogical changes; it is accepted, indeed, that it has done so, namely, in "albitizing" nepheline, introducing microcline, and being responsible for much of the alteration of nepheline to hydrous silicates. A part of the higher silica content of the Bancroft area rocks is therefore due to action by the younger granite. The York River rocks, which are, so to speak, insulated from the granite to the west by beds of limestone and other sediments, appear to be less affected than are the rocks of the Bancroft area. The comparison may best be illustrated in the following fashion:

York River.—Fresh nepheline; potash feldspar scarce, and rocks insulated from the granite

Bancroft area.—Locally much nepheline altered; potash feldspar more abundant, concentrated near joints, faults, and granitic and syenitic dikes; rocks not everywhere protected from the granite

Blue Mountain.—Much nepheline altered; potash feldspar important; rocks surrounded by granite-syenite

The inclusion here of characteristics of Blue Mountain rocks is not intended to imply that the origin of those rocks is taken for granted as being similar to that of rocks of the other areas. In the brief study made of only a part of the Blue Mountain deposit, no evidence was seen which is conclusive one way or another, although the general outline of the alkaline mass, the proved contortion within it that resembles folded stratification, and the close association with certain paragneisses might be construed as favorable to the replacement theory. The apparent distribution of corundum also suggests that it is due to compositional control during the alteration of banded rocks. It was reported, but never verified, that at the southernmost tip the nepheline rock "grades into micaceous paragneisses." Therefore, comparison with other areas is definitely interesting.

NEPHELINE PEGMATITES

The nepheline pegmatites of all areas visited present rather conflicting relations. Their texture is typically pegmatitic, the coarseness of grain size suggesting that volatiles were important in their formation. The common association of calcite-rich bodies have suggested that $CaCO_3$ was also important. Most, if not all, of the substances present in pegmatites are present also in the gneisses.

The pegmatites obviously formed after the nepheline rocks. Some may be explained as replacements, some as recrystallizations, some as intrusives. Certain determination of their origin will come only as a result of much detailed study. The available data are worthy of consideration:

1. Pegmatites cut or replace nepheline rocks.
2. Pegmatites are cut by satellitic dikes of the granitic intrusions.
3. The grain size, contacts, and mineralogy in most cases attest to the presence of volatiles.
4. The common presence of rare elements indi-

cates that those substances were actually concentrated in some medium.

5. Some bodies occur entirely in nepheline rock, some in limestone, and others appear to traverse several types of rock.

We might theorize that some of the pegmatites represent recrystallization ("regeneration") *in situ* in the presence of introduced materials acting as a flux or lubricant; and for some this may be a suitable explanation. But for those pegmatites which replace limestone, the very use of the word "replacement" implies that some agent was available to carry out that process. For those bodies it might be proposed that they were formed in a fashion similar to the development of the nepheline gneisses and that the ultimate concentration of volatiles simply led to pegmatitic textures. But a third group exists, and those appear to have been emplaced by actual intrusion. An example occurs in the York River area, where it is indicated, by surface and drill-core evidence, that nepheline pegmatite truncates the structure of the enclosing gneisses, which are both nepheline-free and nepheline-rich.

There are, then, three types of pegmatite; but all three may be due to the same action, which was in some instances very local and relatively weak but in others was advanced to such a degree that a body of liquid was produced and ensuing movement of the liquid took place in directions determined by structural features.

CONCLUSIONS

This paper is not to be taken as an expression of general dissent from the limestone-syntexis theory. As pointed out by S. J. Shand in a recent publication,[45] there are numerous localities where alkaline rocks are closely associated with limestones, on the one hand, and quartz-bearing igneous rocks, on the other; and in many the evidence is in favor of desilication. We have, however, drawn attention to some earlier misinterpretations in the particular area covered by this study; and, as a result of the corrections, the applicability of the syntexis theory in that area is rendered decidedly doubtful. There is no apparent reason why alkaline rocks cannot form in more than one fashion; in many areas, feldspathoidal magmas are satisfactorily accounted for only by limestone syntexis; in the Bancroft area, the "alkaline rocks" have formed through replacement, and the evidence is not entirely indicative that the replacement was carried out by *nepheline-bearing* solutions that might have formed elsewhere by desilication. The evidence is rather that the solutions were *nepheline-forming* by virtue of the substances they contained and the substances available in the rocks. We cannot show that solutions greatly depleted in silica, even to such a degree that there was insufficient silica to form nepheline, did not originate elsewhere by a reaction similar to the desilication reaction.

In summary, our conclusions may be marshaled in the following fashion:

In the Bancroft and adjacent areas certain horizons of impure calcareous sediments, containing silica, iron, and some alumina, have been modified by the action of a process termed "nephelinization." The process was mechanically analogous to granitization but was chemically different. The nephelinizing solutions at one time or another carried, in particular, soda and alumina, with quantities of volatiles, including H_2O, Cl, P, and others. The exact source of the solutions

[45] "The Present Status of Daly's Hypothesis of the Alkaline Rocks," *Amer. Jour. Sci.*, Vol. CCXLIII*A* (1945) (Daly Volume), pp. 495–507.

is indeterminate, but it was probably a granitic or syenitic magma that is not now recognizable and whose origin and nature are also a matter of question. No definitely intrusive bodies containing nepheline have been observed, excepting a few pegmatitic examples; recrystallization and silication adjacent to fractures have produced anomalous relationships in some instances.

Structural features played an important role in the process; the zones of intense nephelinization were determined by subsidiary folds on the limbs of the major fold.

Most of the pegmatites appear to be replacement bodies, formed, to an unknown extent, through recrystallization ("regeneration") in the presence of "lubricating" mineralizers. Locally, bodies of liquid may have been formed that manifested themselves as pegmatites, which contained variable amounts of nepheline and exhibited intrusive characteristics.

There remain several questions that are imperfectly answered, but they are more or less incidental to the main theme of this paper.

The following succession of events is postulated:

1. Deformation and metamorphism of a series of sediments, consisting of limestones, dolomites, and various rocks of calcareous graywacke type, with the resulting formation of folded structures
2. Formation of nepheline-bearing paragneisses
3. Formation of nepheline pegmatites
4. Intrusion (localized by existing structural features) of granitic magma, with four secondary effects: (*a*) formation of border or contact hybrids from paragneisses; (*b*) formation of syenitic border zones by reaction with several kinds of rock; (*c*) silication (albitization) of nepheline rocks adjacent to rock openings and bedding contacts; and (*d*) some folding and faulting

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ON THE ORIGIN OF CONTINENTS AND OCEAN FLOORS

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ABSTRACT

From the concept of permanence the fundamental question arises as to how the distribution of continental and oceanic sectors came into being. Three groups of theories are discussed: (1) theories starting with a primary surface layer of basaltic composition; (2) theories starting with the resonance theory of the moon's origin and considering the result of such a hypothetical happening on a sialic surface layer of continental thickness; and (3) theories considering the influence of convection currents on a surface layer of sialic composition.

INTRODUCTION

An examination of the Atlantic and Indian oceans and a comparison with the available geological and seismic data show that the bottom of these oceans probably consists of sialic material. On the other hand, the floor of the Pacific appears to be built up of a rigid crystalline layer of basic rocks (crystalline sima). The average depth of the Atlantic appears to be 4–5 km., whereas the North Pacific is generally 1 km. deeper. The explanation seems obvious: viz., the deep depression of the Pacific is controlled by the simatic nature of its bottom; the 1,000-meter higher level of the Atlantic floor is brought about by the presence of a sial-sheet; and the still higher level of the continents is the result of the latter's composition of sial-sheets, which are considerably thicker than the sial-flake under the Atlantic.

The available morphological, geological, and geophysical data cannot be considered as harmonizing either with the hypothesis of a large continental drift in comparatively recent times (Fig. 1, *B*) or with the hypothetical assumption that the floors of the Atlantic and the Indian oceans originated in the Paleozoic, or at an even more recent date, as a result of stretching of continental blocks (Fig. 1, *C*). The hypothesis of large submerged blocks does not agree with the water economy of the oceans (Fig. 1, *A*). For, if the volume of water of the oceans is assumed to have remained relatively stable, the continents would have had to be permanently flooded prior to the foundering of the continental blocks; and this conflicts with all that is known of their geological history. The alternative, viz., that the volume of the oceanic waters has increased by a few cubic kilometers per year, is equally improbable.

The configuration of the continents and oceans has not escaped frequent alterations. Some parts have been submerged, even though such regions as Appalachia, Cascadia, and Scandia were no larger than "borderlands," as Schuchert called them. The idea of permanence is consequently untenable in its extreme sense. But we can speak *cum grano salis* of permanence of the oceans and continents so long as we refrain from constructing huge submerged continents.

These opinions have been stated elsewhere[1] at greater length. The concept of permanency of the oceanic receptacles implies the conviction that these major depressions date from some very early

[1] J. H. F. Umbgrove, *The Pulse of the Earth* (The Hague: Nijhoff, 1942), chap. vi.

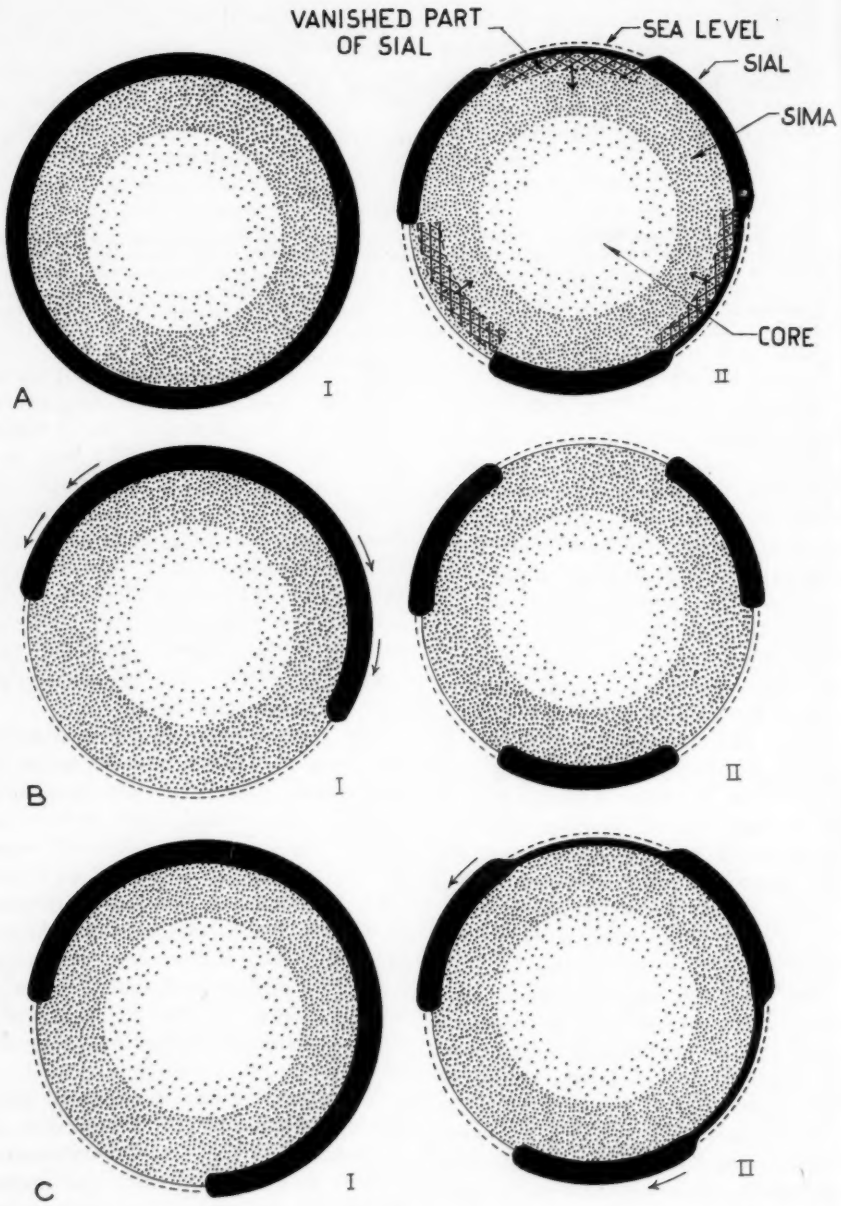

FIG. 1.—Schematic representation of the origin of continents and oceanic receptacles according to the hypotheses of Suess and Haug (*A*), Wegener (*B*), and Bucher (*C*). *I*, Paleozoic condition; *II*, post-Paleozoic movements.

period of the earth's history and that their position has remained essentially unchanged since. But now the question arises as to when and how the "permanent" distribution of continental and oceanic sectors came into being in such a way as to display an antipodal arrangement and a "tetrahedral" plan. What were the factors that caused the concentration of a northern belt of triangular continents, alternating with a southern belt of oceanic units distributed "like a pair of cogwheels with interlocking teeth"?[2] As a matter of fact, thinking of the terrestrial processes that must have operated in the earliest days of our globe's infancy means to enter inevitably a domain which is characterized by scanty available data and therefore widely open to speculation.

It is believed by some geologists, especially by petrologists like Lawson and Rittmann, that the earth's surface in its initial stage was composed of a basaltic melt. It will be interesting to see how they deduced sialic continents from a primary homogeneous surface layer of basic composition.

A second group of theories lays stress on a happening of cosmic importance—the birth of the moon out of the body of the earth. In this group will have to be considered the theories of Osmond Fisher, Pickering, Escher, etc. These students start with a globe surrounded by an outermost layer of sialic rocks of continental thickness, and they try to deduce the origin of continental bucklers and oceanic depressions from the cosmic catastrophe which gave rise to the genesis of the moon in the manner suggested by G. H. Darwin.

Then, in the third place, we will start anew with the idea of a world-encircling layer of sial and try to deduce the desired distribution of continents and oceans without the aid, however, of the hypothetical events of the lunar catastrophe. Some efforts in this direction have been presented recently by the present author and still more recently by Vening Meinesz.

[2] J. W. Gregory, "The Plan of the Earth and Its Cause," *Geog. Jour.*, Vol. XIII (1899), p. 227.

THEORIES OF A PRIMARY SURFACE LAYER OF BASALTIC COMPOSITION

In 1932 A. C. Lawson formulated a theory to account for the formation of continents from a crust which originally consisted of sima only.[3] In his opinion an upper layer of basaltic rocks covered a deeper substratum of dunite. Basaltic continents were produced by orogenic stress. Erosion products from these basaltic continents were carried to the primeval oceans; the basic parts went into a state of solution, while the sialic elements became concentrated; and when these waste products sank sufficiently, they were fused together, so as to form acid granitic rocks. By this process the continents became continually more sialic. Then the sialic material differentiated into a double layer—granite above and diorite below.

Seven years later the Swiss petrologist A. Rittmann[4] introduced a theory which in its main elements is closely akin to that of Lawson. It differs from it, however, in one respect. According to Rittmann, the sialic waste products which assembled in the primeval oceans (Fig. 2) were magmatized by the gases emanating from the substratum. By this process they grew specifically lighter. To restore isostatic equilibrium the

[3] "Insular Arcs, Foredeeps and Geosynclinal Seas of the Asiatic Coast," *Bull. Geol. Soc. Amer.*, Vol. XLIII (1932), pp. 353–82.

[4] "Die Entstehung des Sials," *Geol. Rund.*, Vol. 30 pp. 52–60, 1939.

sialic floors of the primary oceanic receptacles emerged to form sialic continents. On the other hand, the original bucklers of alkali-basalt subsided to form the bottom of the present oceans!

A weak point in both these theories is the formation of the primary basaltic continents. For, in the first place, it is not clear how these protuberances could have formed with preservation of isostatic equilibrium. Nor is it clear how over, the primary disturbance causing the genesis of continental domes out of the basaltic surface layer comes like a *deus ex machina*. Without accepting this initial stage the further deductions of the theory become impossible. Finally, the theories leave the question of the tetrahedral or antipodal plan of terrestrial elements untouched. Nor do they explain the existence of three hypsometric levels, nor the remarkable structural

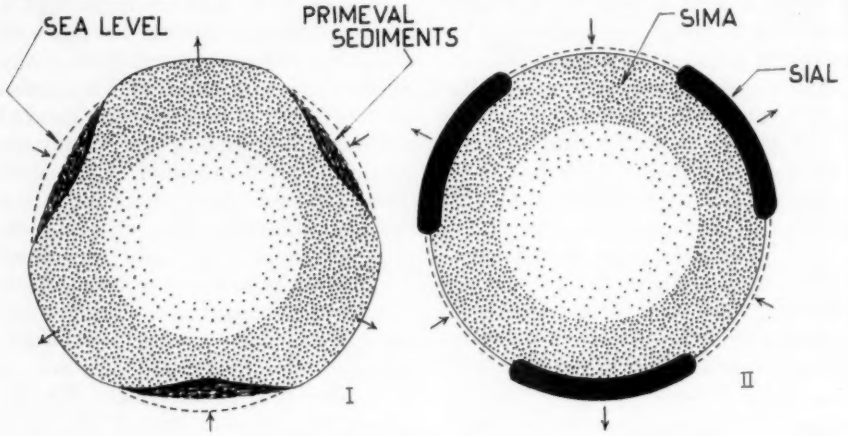

FIG. 2.—Schematic representation of the origin of the continents in the early pre-Cambrian, according to the hypothesis of Rittmann.

these units could have risen isostatically during the long-continued rise above sea-level necessary to provide the primeval oceanic depressions with thousands of meters of erosion products.[5] More-

pattern of the bottom of the Atlantic, etc.

THE RESONANCE THEORY OF THE MOON'S ORIGIN: CONSEQUENCES ON A SIALIC SURFACE LAYER OF CONTINENTAL THICKNESS

It was G. H. Darwin who announced the hypothesis of the moon's origin out

[5] In this respect A. Wade's theory of continental spreading, which is that the spreading starts from a basaltic surface, has some slight advantage. His primeval polar continents were thought to become bare land by the hypothetical process of a retraction of the oceans from the polar areas toward the equatorial belt. The water was supposed to pile up in that region as a result of (1) the greater speed at which the earth rotated on its axis and (2) the greater gravitational pull by the moon, which then was nearer to the earth. According to Wade's theory, the polar continents became covered by a sheet of sial by the "agencies at work which would affect oxidation, hydration, erosion and sedimentation." And he continues: "As soon as these sial-sheets became thick enough and sufficiently consolidated to upset the hydrostatic equilibrium at the poles, both sheets would begin to move and the problem resolves into one concerning two fluids—a lighter one resting on one more dense" ("A New Theory of Continental Spreading," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XIX [1935], p. 1808).

of the body of the earth. Several geologists have tried to imagine the consequences of such a hypothetical birth upon the structural history of the earth's surface layers. If we accept the resonance theory of the moon's origin, it seems highly probable that a great part of the earth's outer shells entered the moon's formation. But what happened to the remaining sialic matter of the earth? There are two possibilities: viz., either the terrestrial remnants of sial were able to flow out and unite again as one continuous shell, enveloping the entire world, or they were unable to do so, being too rigid. The last possibility is basic to the theories of many authors. In their opinion the earth was originally enveloped by a sialic shell of continental thickness. After the moon's disruption the remaining sial-fragments of the earth would have formed our continents, floating on the heavier simatic substratum that forms the bottom of the oceanic receptacles (Fig. 1, *B*). Long ago, the question was raised whether the Pacific might not be considered as a scar brought about by the separation of the moon.

Practically the same idea can be found in the theories of Osmond Fisher, Taylor, Wegener, Schwinner, Escher, and Mohorovicic. The two last-named authors[6] even tried to calculate the thickness of the lunar sial by computing the mass of terrestrial sial that originally filled the gaps of the oceanic sectors. (Both assumed an original crust of continental thickness, and no account was taken of the presence of the sial-flakes of the Atlantic and Indian oceans.)

[6] B. G. Escher, "Moon and Earth," *Proc. Kon. Acad. Wetensch. Amsterdam*, Vol. XLII (1939), pp. 127–38; S. Mohorovicic, "Das Erdinnere," *Zeitschr. f. angew. Geoph.*, Vol. I (1925), pp. 330–83; and *idem*, "Über Nahbeben und über die Konstitution des Erd- und Mondinnern," *Gerland Beitr. zur Geoph.*, Vol. XVII (1927), pp. 180–231.

It is, at all events, clear, however, that neither the continents nor even their so-called "nuclei" (representing the innermost structures of the continents) should be regarded as undisturbed remnants of that distant and turbulent period in our planet's infancy. The "acid slags" had from the early beginning a very complicated history, and the continents (parts of which have been breaking down until quite recently) formerly occupied a more extensive area than they do at present. We know, moreover, that the history of the submarine relief of the oceans is a far from simple one. Another point is that the bottoms of the Atlantic and Indian oceans differ considerably from the floor of the Pacific.

The last important point is, however, taken into account by W. H. Pickering's hypothesis.[7] For, first, his supposition that the scar left on our globe's surface when the moon was torn from the earth's body must be represented by the Pacific explains why that ocean bottom is free of sial. Second, he supposes the scar originally to have been much larger than the present Pacific. "Three-quarters of this crust was carried away," he wrote, "and it is suggested that the remainder was torn in two to form the eastern and western continents." So we could very well imagine that *at this stage* some continental masses drifted apart and that between them the floors of the Atlantic and Indian oceans formed as a result of stretching. Here Pickering's theory is much to be preferred to Wegener's and Du Toit's theories of continental drift. For, in a previous publication[8] much

[7] "The Place of Origin of the Moon: The Volcanic Problem," *Jour. Geol.*, Vol. XV (1907), pp. 23–30, and "The Separation of the Continents by Fission," *Geol. Mag.*, Vol. LXI (1924), pp. 31–35.

[8] Umbgrove, *op. cit.*, p. 96.

stress was laid on convincing arguments which show that, if the floor of the said oceans originated as a result of stretching, this process must have occurred during the early pre-Cambrian and decidedly not since Cambrian, or still less in post-Carboniferous times, as Wegener *cum suis* wished us to believe.

But again the question arises: How did these sial-flakes, drifting apart like large ice floes, come to be settled down in their peculiar tetrahedral arrangement?

Another question of primary importance, however, is: Why should the sialic material have flowed out to form a continuous shell on the moon and not on the earth? The following points should not be forgotten in this connection.

It is questionable, although quite possible, that, prior to the postulated disruption, the sialic material had differentiated into the outer parts of our globe but was not yet in a solid state. Everyone will admit that the outer shells of the earth should have responded readily to deforming tidal forces before, as well as after, the moon's separation. It will also be admitted, if we follow this hypothesis, that part of these outer shells shifted toward the moon and that the scar of the separation was closed smoothly. Moreover, it seems probable that when the earth, recovering from its amputation, was molded into its new shape, the simatic layers—even the uppermost—formed a fluid mass uniting into a continuous shell. It seems, therefore, quite unreasonable to suppose that the thin upper layer of sial would have been the only one incapable of reacting in the same way.[9] The preceding considerations are based on the resonance theory of the moon's origin and are valueless if we accept the opposite view, namely, that the moon and the earth formed simultaneously as two separate bodies.

THEORIES CONSIDERING THE INFLUENCES OF CONVECTION CURRENTS ON A SURFACE LAYER OF SIALIC COMPOSITION

Once more our considerations may be based on the supposition that the earth was initially enveloped by a continuous sialic layer, gradually solidifying and floating on a denser basic substratum.[10] It may be that this layer formed after the moon's disruption, but it might similarly be assumed that the moon had not severed from the earth.

According to the present author, the only plausible way in which continental blocks might have originated from a world-encircling sialic layer, growing gradually cooler and solidifying, is that a process of thickening occurred, resulting from folding and drifting, due to the action of convection currents.

This process shortens the sialic layer, and sial-free parts (such as large portions of the present Pacific area) were therefore formed. Figure 3 *A–C* shows diagrammatically how a continent may possibly have originated through periodical buckling and drifting of an originally thin sialic layer enveloping the whole earth.

It may be that during the process of the drifting of these primordial continents a sial-sheet was torn into two or

[9] Even the lighter simatic material would have been lacking in the Pacific sector, according to Schwinner, and this would have prevented the sialic layer from covering this area. The fact, however, that the Pacific's volcanoes are built up of basaltic material clearly shows that this opinion cannot be upheld.

[10] A similar concept of a layer of sial which originally encircled the world is held by Bowie; Geszti; Daly (1938), p. 176; and Wegener (4th ed., 1929), p. 207.

more parts, each moving in a different direction and producing one or more thinly stretched sial-flakes between them (Fig. 3, *D*). In this way (and only during these primordial times) a thin sial-sheet like that which probably exists under the Atlantic may possibly have originated as a result of stretching of either a primordial continent or the intervening primary sial-layer. There is reason to believe that this process actually happened. For, if the sial of our present con-

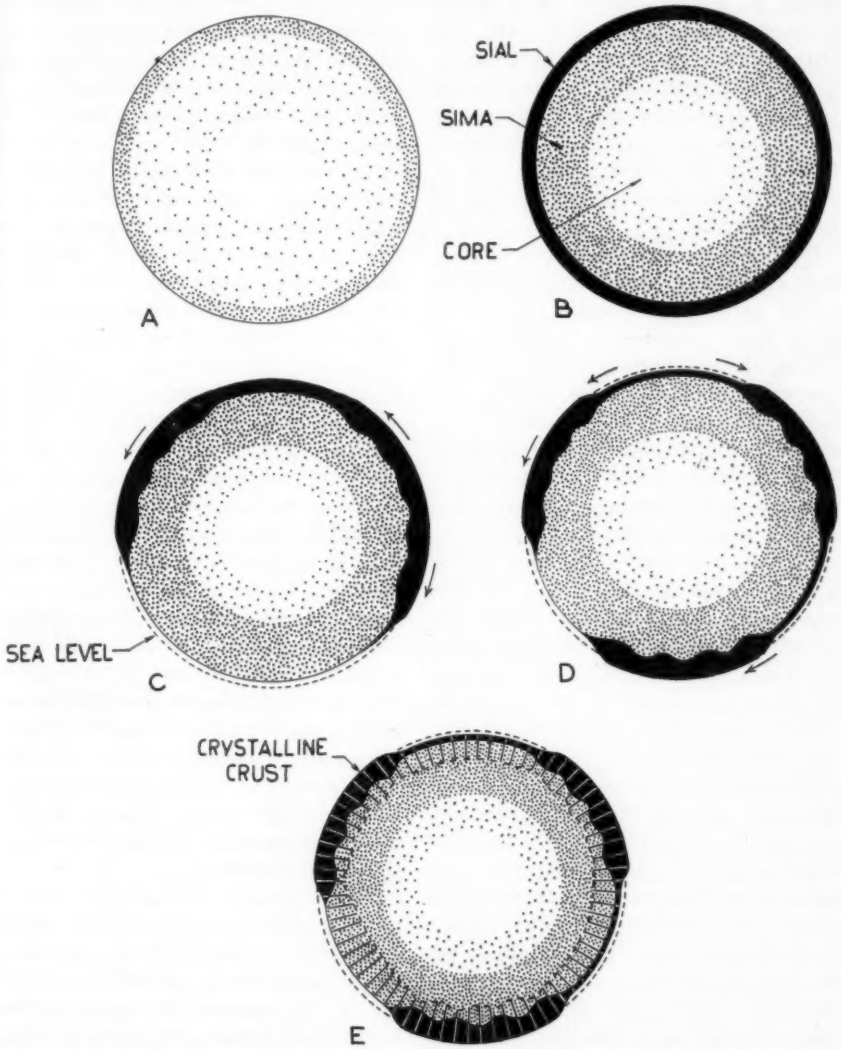

FIG. 3.—Schematic representation of the origin of continents and oceanic receptacles in the early pre-Cambrian by a process of buckling and drifting of an originally sialic layer enveloping the whole earth.

tinents were imagined as spreading out as thickly as the sial-layer of the Atlantic, it would probably cover a larger area than that of the present sial-free ocean bottoms. A floor such as that of the Atlantic cannot, therefore, be regarded as a remnant of the primary world-encircling sialic shell. On the contrary, it would seem to have grown thinner as a result of stretching during the early pre-Cambrian. It would be impossible to say, just now, whether a fragment of the primary sialic layer of original thickness exists in some part of the world today.

It is obvious that this process must have attained its most important effect in the early pre-Cambrian, since the whole later process of buckling and folding of the continents is known to have evolved only in these existing pre-Cambrian bucklers. This is, indeed, remarkable and will have to be examined before any other features are discussed.

In the beginning the continents grew steadily larger; but this has not been repeated since at least the Cambrian, or probably even earlier times, as the geosynclines and folded chains that are known to have formed since then originated in a basement which had already been folded previously.[11]

Hence we cannot escape the conclusion that some event of fundamental importance must have occurred during the early part of the earth's history, causing the surface history of primeval times to differ from that of subsequent periods. By this we mean that from a certain critical moment onward continental growth in a "horizontal" direction ceased. The most plausible explanation seems to be that the world-encircling solid crust had become so thick that subsequent growth was no longer possible. Such youthful caprices as are illustrated in Figure 3, *A–D*, may be expected to have ended as soon as the earth had attained a physical state more or less resembling that which it has at present (Fig. 3, *E*). From that time onward the terrestrial forces were imprisoned and became operative as subcrustal processes.

At that time the crust consisted of basic rocks in the sial-free parts of the surface just as it does now; and it may have contained both sialic and simatic rocks in those regions of the world where sial-flakes were present. It must have been of varying thickness, though it need not, of course, have equaled its present-day thickness. We will call this state the "consolidated surface of the earth." A few years ago W. Bowie[12] formulated his opinion regarding a primeval process of crustal buckling as follows: "It is impossible on a molten earth gradually cooling to have the light material which must have been present around the whole earth, pushed together into great masses to form continents. There is no force available inside or outside the earth which could have caused such a segregation of surface matter."

As mentioned before, the process of folding and drifting of the sialic surface layer is ascribed by us to the action of convection currents. Their periodical occurrence must at one time have found the sial-sheet cooled and solidified to such a degree that the result was continental thickening.

If the foregoing hypothesis may be said to contain a germ of truth, the problem of the continents and ocean floors would consequently be associated with periodic phenomena of crustal folding, which had, however, already produced their main results in the early pre-

[11] A fuller illustration of the preceding consideration will be found in chap. ii and the Appendix of Umbgrove, *op. cit.*

[12] "The Origin of Continents and Oceans," *Sci. Monthly*, Vol. XLI (1935), p. 447.

Cambrian. A few points will now be examined more closely.

Let us consider the moment that these primeval surface features became petrified, as it were, by the formation of a world-encircling solid crust of sufficient thickness.

The noteworthy structural pattern of the floor of the Atlantic and the surrounding continents probably originated in the early pre-Cambrian, for the old structural lines repeatedly influenced tectonic phenomena in later times. It might therefore be asked whether it is not obvious that this ancient pattern dates from the period of consolidation of a solid crust. In the preceding paragraphs we stated that three favored levels occur on earth, represented by (1) the continental surface, (2) the floor of the Atlantic, and (3) the bottom of the Pacific Ocean. It need hardly be said that these features fit well with our working hypothesis. The difference in the level of the primeval floors of the Pacific and Atlantic is seemingly due to the difference of the materials composing each floor.

On the other hand, buckling of the primordial sialic crust was responsible for the continental thickenings. Their remarkable thickness and high level, as compared to that of the bottom of the Atlantic, is controlled by five factors, viz. (1) the thickness of the original world-wide sialic layer, (2) the compressive forces during the periodic phases of early pre-Cambrian buckling, (3) the leveling effect of subaerial erosion, (4) the pre-Cambrian stretching of sial-sheets of the Atlantic type, and (5) the local thickening of the continental basement complex as a result of the formation of later geosynclines and mountain belts.

The above considerations indicate the main outlines of the new working hypothesis. I do not wish to suggest that this hypothesis solves the intricate problem of the ocean floors. I merely followed a line of thought which had hitherto been neglected; and, as all the previous hypotheses are deficient in many respects, the new hypothesis may stimulate others in their efforts to unravel the mystery of the ocean floors. I fully realize how many difficulties are inherent in this new aspect of the old problem.

It will be seen that some of the most attractive aspects of the theory were explained as well by Pickering's hypothesis. And the weak points in both theories are again the same. For no adequate explanation was given for the antipodal distribution of the major units of the earth's surface, nor for the triangular shape of these elements.[13]

Quite unexpectedly, however, a mathematical and geophysical treatise by F. A. Vening Meinesz seems to throw

[13] I would like to elucidate a few remaining points. The hypothesis to which we referred above is based on the assumption that a continuous sialic layer, which was originally enveloped by a thin layer of water, extended over the entire world. Oceanic basins with a steadily increasing volume of water originated *ipso facto* as the continental blocks were created. It would, consequently, be wrong to presume that the continents emerged from the deep sea and that we might therefore expect to find the continents covered by a veneer of deep-sea sediments. On the contrary, deep-sea deposits are known to be almost nonexistent in the present continents. Yet this cannot be said to conflict with our working hypothesis, the more so as the volume of water has undoubtedly grown since primeval times.

The whole history of geosynclines and folded chains since the pre-Cambrian took place on a basement which had already been folded during the pre-Cambrian. It is impossible to describe the subcrustal processes which were responsible for the distribution and sequence of folding of the continents. It is evident, however, that a repeated buckling of continental areas—a process which may possibly also have taken place in the pre-Cambrian—must have caused the lower side of the continents to become extremely irregular. This feature is, in fact, corroborated by both seismic data and the different altitudes of the mountain belts, which are more or less in a state of isostatic equilibrium.

some light on this side of the problem.[14] In 1944 he published a preliminary paper on the distribution of continents and oceans. The main line of his argumentation runs as follows: It is supposed that a system of convection currents must have come into existence during the primordial phase of cooling of the earth. One possibility is that the rising currents carried sialic components to the surface, where these acid constituents become arranged in a very peculiar manner, viz., in such a way that the breadth of a current is double its height. Admitting that the terrestrial system, at least in a primordial stage of cooling, reached down to a depth of 2,900 km., Meinesz found as their most probable distribution: eight currents, four rising ones alternating with four descending currents. Hence, each current ought to occupy an octant of the outer parts of the globe,

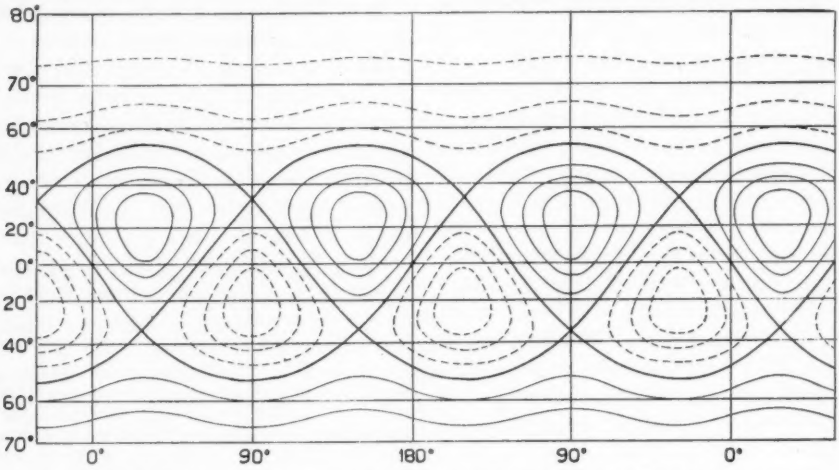

FIG. 4.—Distribution of convection currents during the primordial phase of cooling of the earth. Areas of rising currents are indicated by full-drawn lines; areas of descending currents, by dotted lines (afterMeinesz).

solidified *in loco*, no further displacements taking place on the surface. It fails, therefore, to explain the well-known characteristic differences between the floor of the Atlantic and Indian oceans and the bottom of the Pacific. Another possibility is based on our above-mentioned theory of an original continuous layer of sial enveloping the whole world. There the sialic layer was thought to have been thrust together by the action of subcrustal convection currents. Then Meinesz tried to prove that the system of convection currents had to and it seems plausible to suppose that the axis of two of these octants coincided with the rotation-axis of the earth. The resulting distribution is shown by Figure 4 in Mercator projection. This remarkable result suddenly seems to make clear how the antipodal distribution and the triangular shape of the major terrestrial elements possibly came into being. For the figure clearly shows how these features are graphically represented in the scheme as a necessary result of the mathematical formulas.

Future investigations will undoubtedly bring more unexpected data and still other theoretical points of view.

[14] "De Verdeeling der Continenten en Oceanen over het Aardoppervlak," *Versl. Nederl. Akad. v. W.*, Vol. LIII (1944), pp. 151–59.

PREGLACIAL EROSION SURFACES IN ILLINOIS[1]

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ABSTRACT

A generalized map of buried erosion surfaces in Illinois, compiled from detailed maps of the bedrock topography, provides regional perspective for recognition and correlation of erosion surfaces within the state. A correlation of the Lancaster peneplain of northwestern Illinois, the Calhoun peneplain of western Illinois, and the Ozark peneplain of northern Illinois is suggested; an independent lower surface which developed on the weak rocks of the Illinois basin is described and named the "Central Illinois peneplain"; and possible straths along major preglacial valleys are recognized and named the "Havana strath."

INTRODUCTION

Because of the cover of glacial drift, studies of erosion surfaces in the Mississippi Valley region have been restricted largely to the Driftless Area and to the uplands lying outside the limits of glaciation. Studies in Illinois, which concern (1) the Driftless Area of northwestern Illinois, (2) Calhoun County in western Illinois, and (3) the southern unglaciated section, are summarized briefly in the following pages. A few attempts have been made to correlate buried bedrock uplands in local areas within the glaciated region, but there has been no regional treatment of the problem. In the present study a groundwork for regional interpretation was provided by a detailed bedrock-surface map of Illinois, which was compiled in connection with ground-water studies. A generalized contour map of the erosion surfaces (Fig. 1) summarizes the essential features revealed by the detailed map.

The detailed bedrock-surface map was compiled from about 60,000 records of borings within the state and from all available data on the location of bedrock exposures. In areas where the drift is thin, the present topography, shown by topographic maps, revealed the major features of the bedrock surface. The original maps for about half the state were compiled on topographic sheets and contoured with intervals of 10, 20, and 25 feet. For the remainder of the state, where less control was available, 50-foot contours were drawn on a base map having a scale of 4 miles to the inch. The final map of the entire state was drafted on the latter scale.

The generalized map of the erosion surfaces was drawn from the detailed map by connecting points of equal elevation on interstream areas. It thus shows the general form of the uplands before dissection and could be considered an attempted reconstruction of a late Tertiary land surface somewhat modified by later fluvial and glacial erosion. The element of personal judgment enters into the selection of broad valleys that are to be shown or eliminated, otherwise the contours are closely controlled by numerous points on the divides. This method applied to the upland terraces of southern New England was found to show the same major features as those revealed by multiple projected profiles of the same area.[2]

[1] Published with the permission of the chief of the Illinois Geological Survey, Urbana, Illinois.

[2] George F. Adams, "Upland Terraces in Southern New England," *Jour. Geol.*, Vol. LIII (1945), p. 309.

PREVIOUS STUDIES OF EROSION SURFACES IN ADJOINING DRIFTLESS AREAS

NORTHWESTERN ILLINOIS

The upland surfaces in the Driftless Area of the upper Mississippi Valley have been studied intensively for the last fifty years and are better known than other erosion surfaces in the interior of the continent.[3] Yet there is no general agreement as to the number of cyclical surfaces present or their age. Interpretations have ranged from noncyclical development during a single period of erosion[4] to recognition of five distinct cyclical surfaces.[5] Most writers have identified remnants of either one or two peneplains.

[3] O. H. Hershey, "Preglacial Erosion Cycles in Northwestern Illinois," *Amer. Geol.*, Vol. XVIII (1896), pp. 72–100, and "The Physiographic development of the Upper Mississippi Valley," *ibid.*, Vol. XX (1897), pp. 246–68; U. S. Grant and E. E. Burchard, "Lancaster–Mineral Point Folio, Wisconsin-Iowa-Illinois," *U.S. Geol. Surv. Geol. Atlas, Folio 145* (1907), p. 2; A. C. Trowbridge, "Some Partly Dissected Plains in Jo Daviess County, Illinois," *Jour. Geol.*, Vol. XXI (1913), pp. 731–42; E. W. Shaw and A. C. Trowbridge, "Galena-Elizabeth Folio, Illinois-Iowa," *U.S. Geol. Surv. Geol. Atlas, Folio 200* (1916), pp. 9–10; A. C. Trowbridge and E. W. Shaw, "Geology and Geography of the Galena and Elizabeth Quadrangles," *Ill. Geol. Surv. Bull. 26* (1916), pp. 136–46; U. B. Hughes, "A Correlation of the Peneplains of the Driftless Area," *Proc. Iowa Acad. Sci.*, Vol. XXIII (1916), pp. 125–32; A. C. Trowbridge, "The Erosional History of the Driftless Area," *Iowa Univ. Studies*, 1st ser., No. 40 ("Studies in Nat. Hist.," Vol. IX, No. 3 [1921]), pp. 55–127 (the most detailed study of the problem; contains a complete bibliography up to 1921); Lawrence Martin, "Physical Geography of Wisconsin," *Wis. Geol. Surv. Bull. 36* (2d ed., 1932), pp.69–77; A. C. Trowbridge, in *Kansas Geological Society Guide Book, Ninth Annual Field Conference, Upper Mississippi Valley* (Wichita: Kansas Geological Soc., 1935), pp. 62, 75; F. T. Thwaites, in *Kansas Geological Society Guide Book . . . .*, pp. 105–26; R. E. Bates, "Geomorphic History of the Kickapoo Region, Wisconsin," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 820–41.

[4] Martin, ftn. 3.

[5] Hershey, ftn. 3.

In the Illinois section of the Driftless Area two prominent upland surfaces are present. The upper surface, termed the "Dodgeville peneplain,"[6] is represented by the tops of narrow ridges and isolated mounds capped by Silurian dolomite which are 1,000–1,150 feet above sea-level and 350–450 feet above drainage. The lower surface, called the "Lancaster peneplain,"[7] lies about 200 feet below the Dodgeville plain and is of greater extent than the older surface. It coincides closely with the top of the Ordovician Galena dolomite and slopes southwestward from about 950–800 feet above sea-level (Figs. 3 and 4).[8]

Gravels of the Windrow formation are found on remnants of the Dodgeville peneplain in adjoining states,[9] but only scattered pebbles, occurring at various elevations, have been found in Illinois.[10] Nebraskan drift is reported to be present on both upland surfaces in Iowa but has not been discovered in valleys eroded below the Lancaster plain. This relation led Trowbridge[11] to conclude that the lower surface was undissected at the

[6] Named from the upland near Dodgeville, Wisconsin, by Trowbridge (p. 64 of ftn. 3 [1921]). Trowbridge now regards the Dodgeville plain as part of the lower Lancaster peneplain rather than as an independent erosion surface (personal communication [1946]).

[7] Named from Lancaster, Wisconsin, by Grant and Burchard, p. 2 of ftn. 3.

[8] Both surfaces are well shown on the Galena and Elizabeth quadrangle maps.

[9] R. D. Salisbury, "Preglacial Gravels on the Quartzite Range near Baraboo, Wisconsin," *Jour. Geol.*, Vol. III (1895), pp. 665–67; Trowbridge, pp. 111–13 of ftn. 3 (1921); F. T. Thwaites and W. H. Twenhofel, "Windrow Formation: An Upland Gravel Formation of the Driftless and Adjacent Areas of the Upper Mississippi Valley," *Bull. Geol. Soc. Amer.*, Vol. XXXII (1920), pp. 293–314.

[10] Trowbridge, p. 112 of ftn. 3 (1921); H. B. Willman, personal communication (1946).

[11] Pp. 123–25 of ftn. 3 (1921) and pp. 62, 75 of ftn. 3 (1935).

time of Nebraskan glaciation. However, the possibility of subsequent removal of the drift from the valleys cannot be eliminated altogether, and the surface may have been dissected at an earlier date. This alternative is indicated by the occurrence of Kansan and possibly Nebraskan drift within deep bedrock valleys of the ancient Mississippi and its tributaries (Fig. 5) in the central part of the state.[12] A compromise view that the deep valley of the ancient Mississippi in the Driftless Area is younger than the deep valley to the south has not been supported by preliminary subsurface studies in the intervening area.

CALHOUN COUNTY, WESTERN ILLINOIS

The narrow upland peninsula between the Mississippi and the Illinois rivers above their junction in western Illinois is driftless except for loess deposits, and two erosion surfaces in the area have been described by W. W. Rubey.[13] An upper surface, forming the crest of the upland at an elevation of 700–750 feet, was named the "Calhoun peneplain," and an intermediate level, 125–250 feet lower, was described as a postmature surface (Fig. 1). The Lincoln Hills, in the adjoining area in Missouri, rise 100–200 feet above the higher surface. The higher surface is largely on Osage (Mississippian) limestones, and to the north it bevels structure. Gravels of "Lafayette type," composed of chert, quartz, and quartzite in a ferruginous matrix, are present on the upper surface north of the Cap au Grés faulted flexure and on a lower upland about 600 feet above sea-level south of the flexure in the southern tip of the county (Fig. 1).[14] This relation raises the question of whether there was important movement along the Cap au Grés fault after deposition of the gravels, as concluded by Rubey,[15] or whether gravels, possibly of different age, were deposited on two distinct surfaces.

SOUTHERN ILLINOIS

The driftless section of southern Illinois roughly includes the area lying south of the Pennsylvanian (Caseyville) escarpment, which extends east-west completely across the southern tip of the state (Fig. 1). Within this region there are two important uplands which are structurally and topographically distinct: (1) the Shawnee section, which includes the Pennsylvanian cuesta and adjoining lower surfaces on the south, and (2) an isolated segment of the Salem plateau of the Ozark region margining the Mississippi trench along the west side of the area.[16] The upland surfaces in the Shawnee section occur at several levels, on various bedrock formations which have been extensively faulted and probably include undifferentiated cyclical and structural surfaces. The uplands of the Salem plateau, in contrast, rise to accordant levels about 700 feet above sea-level and are underlain almost exclusively by deeply weathered Devonian cherts.

No detailed studies have been made of the entire district, and attempted cor-

[12] Leland Horberg, "A Major Buried Valley in East-central Illinois and Its Regional Relationships," *Jour. Geol.*, Vol. LIII (1945), pp. 353–55; unpublished sample study records in the files of the Illinois Geological Survey.

[13] "Geology and Mineral Resource of the Hardin-Brussels Quadrangles, Illinois," unpublished manuscript (1931).

[14] Rubey, ftn. 13; R. D. Salisbury, "On the Northward and Eastward Extension of the Pre-Pleistocene Gravels of the Mississippi Basin," *Bull. Geol. Soc. Amer.*, Vol. III (1892), pp. 183–86; Stuart Weller, "Notes on the Geology of Northern Calhoun County," *Ill. Geol. Surv. Bull. 4* (1907), p. 231.

[15] Ftn. 13.

[16] N. M. Fenneman, *Physiography of Eastern United States* (New York: McGraw-Hill Book Co., Inc.. 1938), pp. 438–39, 651–52, Pl. VI.

relation must be based on studies of two local areas and on broad regional relations. As the result of studies by R. D. Salisbury[17] in Hardin County at the eastern edge of the Shawnee Hills, and by J. E. Lamar[18] in the Carbondale quadrangle in the western part, four erosion surfaces ranging in elevation from 500 to 900 feet have been described, as shown by Table 1. The surface 700–760 feet above sea-level, described by Lamar, appears to be most extensive, and it is probably this surface which R. F. Flint[19] recognized as part of the domed Ozark peneplain and correlated with the Highland Rim surface in Kentucky and Tennessee, and which N. M. Feneman,[20] in addition, correlated with the Lexington peneplain of Kentucky and the Lancaster peneplain in the Driftless Area. The surface is believed by Flint[21] to transect Wilcox (Eocene) strata and therefore to have been completed sometime during the Tertiary. It is significant that the Devonian formations of the Salem Plateau have been weathered and leached to depths of about 400 feet and that this unusual depth of alteration has been ascribed by J. M. Weller[22] to a possible prolonged alteration under peneplain conditions.

The generalized contour map of the upland surfaces (Fig. 1) suggests (1) the presence of a widespread surface about 700 feet above sea-level that is correlative with the Ozark peneplain, and (2) restricted higher-summit areas which may represent remnants of the Buzzards Point plain or monadnocks on the lower surface. Lower surfaces, 500–550 feet and 600–650 feet in elevation, in the central part of the area may represent the McFarlan and Karbers Ridge plains, respectively, or they may be primarily structural plains.

Lafayette-type gravel occurs on the Salem Plateau in Union County,[23] on the Pennsylvanian escarpment in Gallatin County,[24] and on the crests of hills

TABLE 1

EROSION SURFACES IN SOUTHERN ILLINOIS

HARDIN COUNTY (SALISBURY)		CARBONDALE QUADRANGLE (LAMAR)	
Name	Elev.	Elev.	Name
Present flood plains	320–340	320–350	Present flood plains
Elizabethtown plain	400–420		
McFarlan plain	500–540	500–560	McFarlan plain(?)
Karbers Ridge plain	600–640	600–650	Karbers Ridge plain(?)
		700–760	Unnamed
Buzzards Point plain	860–900	800–860	Buzzards Point plain(?)

[17] Stuart Weller, Charles Butts, L. W. Currier, and R. D. Salisbury, "Geology of Hardin County," *Ill. Geol. Surv. Bull. 41* (1920), pp. 47–52.

[18] "Geology and Mineral Resources of the Carbondale Quadrangle," *Ill. Geol. Surv. Bull. 48* (1925), pp. 152–54.

[19] "Ozark Segment of Mississippi River," *Jour. Geol.*, Vol. XLIX (1941), pp. 634–36, 640.

[20] Pp. 441, 504, and 660 of ftn. 16.

[21] Pp. 639–40 of ftn. 19.

[22] "Devonian System in Southern Illinois," *Ill. Geol. Surv. Bull 68A: Devonian Symposium* (1944), pp. 101–2.

[23] J. M. Weller, personal communication (1945).

[24] Charles Butts, "Geology and Mineral Resources of the Equality-Shawneetown Area," *Ill. Geol. Surv. Bull. 47* (1925), p. 52.

and ridges at lower elevations south to the Ohio valley (Fig. 1). Because of the presence of a weathered zone up to 6 feet thick on the Lafayette and below the loess, J. M. Weller[25] has concluded that deposition of Lafayette gravels was followed by a long period of stable conditions, under which weathering progressed, and that the major period of bedrock erosion giving rise to the present topography occurred during the final part of the post-Lafayette preglacial interval.

BURIED EROSION SURFACES

GALENA UPLAND SURFACE

Description.—The summit areas of the preglacial Galena upland in north-central and northwestern Illinois form a remarkably uniform plain, which slopes southeastward from 950 feet above sea-level at the edge of the Driftless Area to about 800 feet at the south edge of the upland (Lancaster peneplain, Fig. 1). The gradient is about 3 feet per mile, and local relief on the restored surface in most places is less than 50 feet. A broad, upland crest, which extends southeastward across the southwestern part of the upland, coincides closely with the preglacial divide between the ancient Mississippi and Rock River drainage systems (Fig. 5). Along the south and east margin of the upland there is a break in upland profiles between elevations of 800 feet on the north and 650 feet on the south. The zone along which the change occurs is about 20 miles wide and is independent of structure. Along it is drawn the boundary between the Lancaster and Central Illinois peneplains (Fig. 1).

Relation to structure.—The upland plain is developed largely on the Galena dolomite, although in only a few places does it coincide closely with the upper part of the formation. Comparison of the generalized bedrock-surface contours with structure contours of similar interval on the top of the Galena (Figs. 1 and 2) shows that in the western half of the upland the rock surface is generally 150 feet or more below the top of the dolomite, and that to the east the surface crosses onto the overlying Maquoketa shale and lies 100 feet or more above the top of the Galena dolomite. In various local areas the surface is eroded on beds ranging in age from Silurian (Niagaran dolomite) to Cambrian (Trempealeau dolomite).

When the structural and topographic trends are compared, a further lack of coincidence is revealed. The regional slope of the upland is roughly S. 30° E., whereas the three major structural trends are north-south along the Wisconsin arch, east-west along the Savanna-Sabula anticline, and N. 60° W. along the positive element between the Sandwich fault zone and the LaSalle anticline (Fig. 2). Locally there are several places where beveling of structure is indicated: (1) across the Savanna-Sabula anticline and the syncline to the north, (2) across the northwest flank of the LaSalle anticline near its juncture with the Savanna-Sabula anticline in southwestern Ogle County (3) across the northern end of the Sandwich fault zone and related structures in southeastern Ogle and northeastern Lee counties, and (4) across numerous minor folds which plunge down regional dip on the east flank of the Wisconsin arch.

It is concluded that there is only a gross relation between structure and the upland surface and that, in detail, the transgressions of structure are so numerous and important that the surface can-

[25] "Geology and Oil Possibilities of Extreme Southern Illinois," *Ill. Geol. Surv. Rept. Investigations 71* (1940), p. 4.

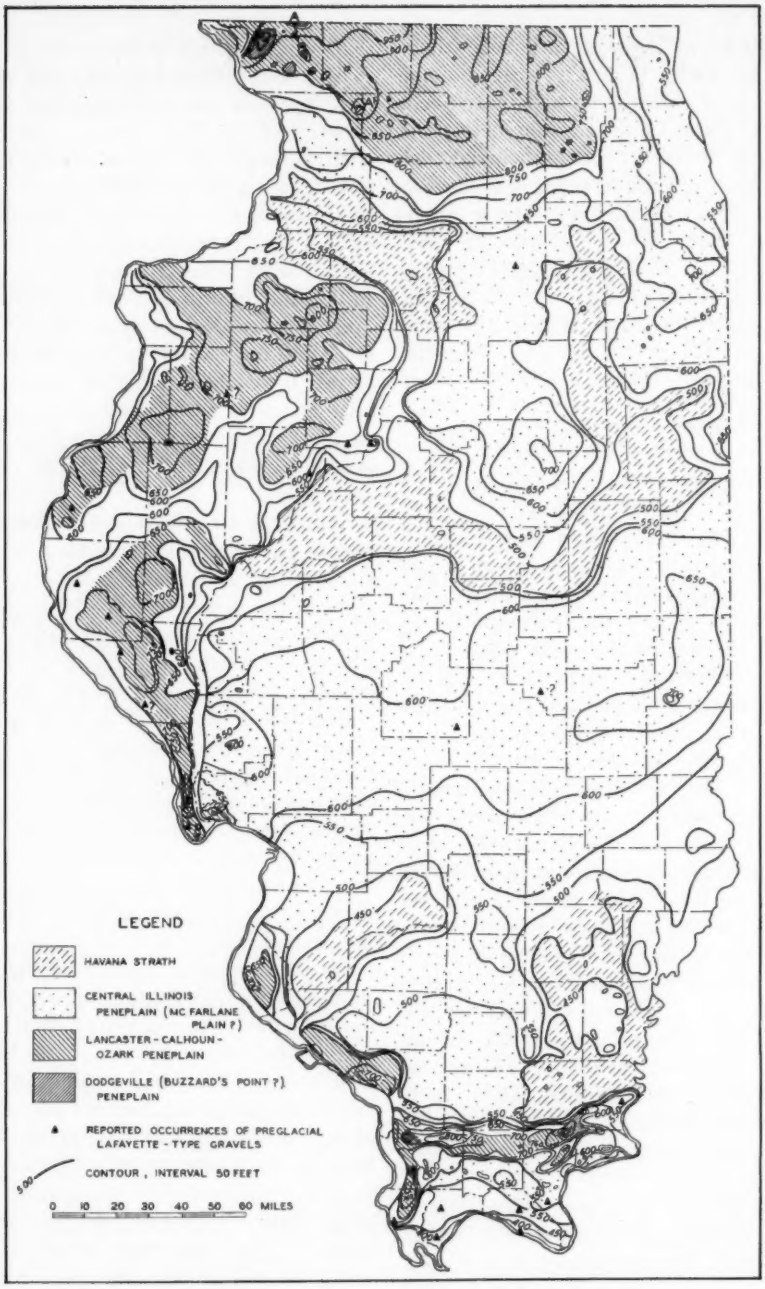
LEGEND
HAVANA STRATH
CENTRAL ILLINOIS PENEPLAIN (MC FARLANE PLAIN ?)
LANCASTER - CALHOUN - OZARK PENEPLAIN
DODGEVILLE (BUZZARD'S POINT ?) PENEPLAIN
REPORTED OCCURRENCES OF PREGLACIAL LAFAYETTE - TYPE GRAVELS
CONTOUR, INTERVAL 50 FEET
0 10 20 30 40 50 60 MILES

FIG. 1.—Generalized contour map of the erosion surfaces in Illinois

not be considered a simple structure plain.

Correlation.—The Galena upland plain within the drift-covered area was recognized previously[26] and interpreted as modified remnants of what is now generally regarded as the Lancaster or late Tertiary peneplain. This conclusion is substantiated by the present study.

The alternative—that the surface represents the higher Dodgeville peneplain—is possible if downwarping is postulated; and it is supported indirectly by Bates,[27] who concluded from a study of projected profiles in the Driftless Area that the Lancaster peneplain of Trowbridge is a stripped structural plain rather than a cyclical surface. This conclusion appears to be justified by relations in the Illinois section of the Driftless Area, where the Lancaster peneplain coincides closely with the top of the Galena dolomite. However, if it is the Lancaster surface that extends southeastward below the drift and bevels structure on the Galena upland, the cyclical origin of the surface finds new support. In fact, one of the strongest evidences of beveling is found just south of the drift margin, where the Maquoketa shale and Silurian dolomite along the syncline north of the Savanna-Sabula anticline are truncated by the bedrock surface (Fig. 3).

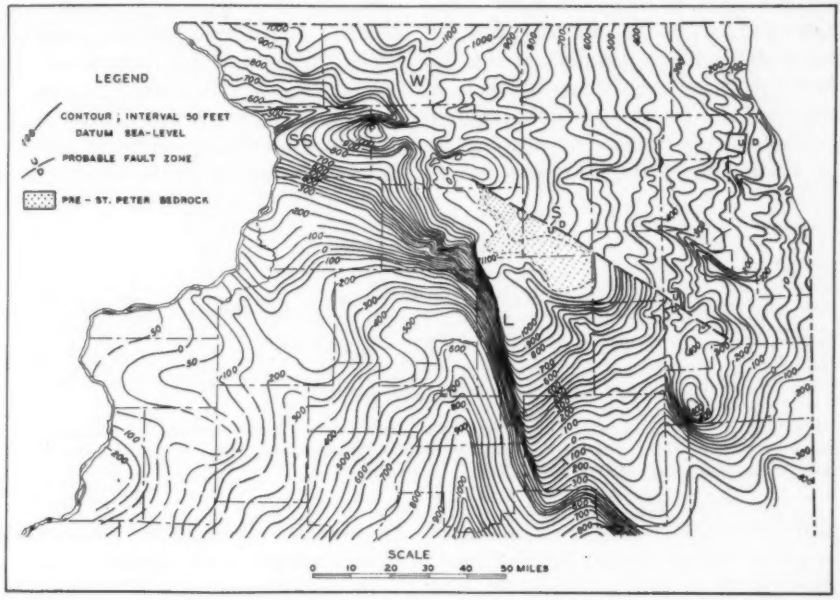

FIG. 2.—Structure contours on top of the Galena dolomite in northern Illinois. *W*, Wisconsin arch; *S-S*, Savanna-Sabula anticline; *S*, Sandwich fault zone; *L*, LaSalle anticline.

[26] Hershey ftn. 3 (1896) (1897); J H. Bretz, "Geology and Mineral Resources of the Kings Quadrangle," *Ill. Geol. Surv. Bull. 43* (1923), pp. 273–77; R. S. Knappen, "Geology and Mineral Resources of the Dixon Quadrangle," *Ill. Geol. Surv. Bull. 49* (1926), pp. 90–93.

[27] Pp. 833–37 of ftn. 3.

In an attempt to determine whether this bedrock surface represents the Lancaster or the Dodgeville surface, a generalized contour map covering most of the Driftless Area in Illinois was constructed from topographic sheets (Fig. 4). The reconstruction indicates (1) that the Dodgeville upland in its northern part is delimited from Lancaster surfaces to the east and west by clearly defined escarpments but that to the south there is no sharp break to a lower surface; (2) that possible isolated remnants of the Dodgeville peneplain in the south half of the Elizabeth quadrangle are distinct from the Lancaster surface on the north but descend more gradually to a lower surface on the south; (3) that the Lancaster surface in the northern half of the Elizabeth quadrangle continues eastward below the drift and possibly southward onto the uplands of the Savanna quadrangle. Relations 1 and 2 suggest the possibility that the Dodgeville peneplain is downwarped to the south and that the Lancaster could be a local southwest-sloping structural plain. However, it appears to be the Lancaster surface which continues eastward into the area where the buried Galena upland surface is best developed (Fig. 1). Because of this, the Galena upland surface is correlated with the Lancaster peneplain.

UPLAND SURFACES IN WESTERN ILLINOIS

Description.—The bedrock uplands in western Illinois are less continuous and more variable in elevation than those of the Galena upland to the north and the Pennsylvanian lowland to the east. They appear to represent a broad, mature surface, on which there are possible remnants of a summit peneplain 700–800 feet above sea-level and possibly a lower surface 600–650 feet above sea-level (Fig. 1). The upper surface is interrupted by two broad valleys, so that it is not continuous from north to south. Possible remnants of the lower surface are present only along the northern and eastern margin of the upland.

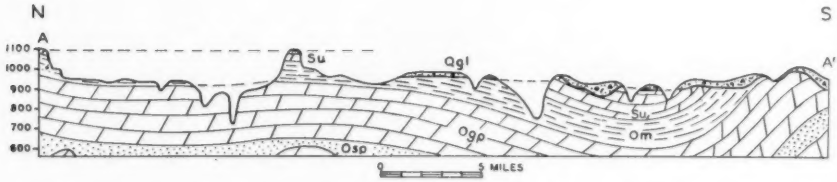

FIG. 3.—Cross-section showing Dodgeville (*upper*) and Lancaster (*lower*) surfaces in northwestern Illinois along *A–A'* of Fig. 1. *Qgl*, glacial drift; *Su*, Silurian dolomite; *Om*, Maquoketa shale; *Ogp*, Galena-Platteville dolomite; *Osp*, St. Peter sandstone.

In the western part of the area the upper surface is continuous from weak Pennsylvanian beds on the east to resistant Mississippian (Meramec and Osage) dolomites to the west. Actually, the highest elevations are on Pennsylvanian strata near the northwest corner of the upland. The high elevation of the upland as a whole compared with the lowland to the east cannot be explained by differential erosion, as there are no important differences in the compositon of the Pennsylvanian rocks in the two areas. Nor is there any marked difference in drainage position, since the higher upland is essentially surrounded by major preglacial valleys. One possible explana-

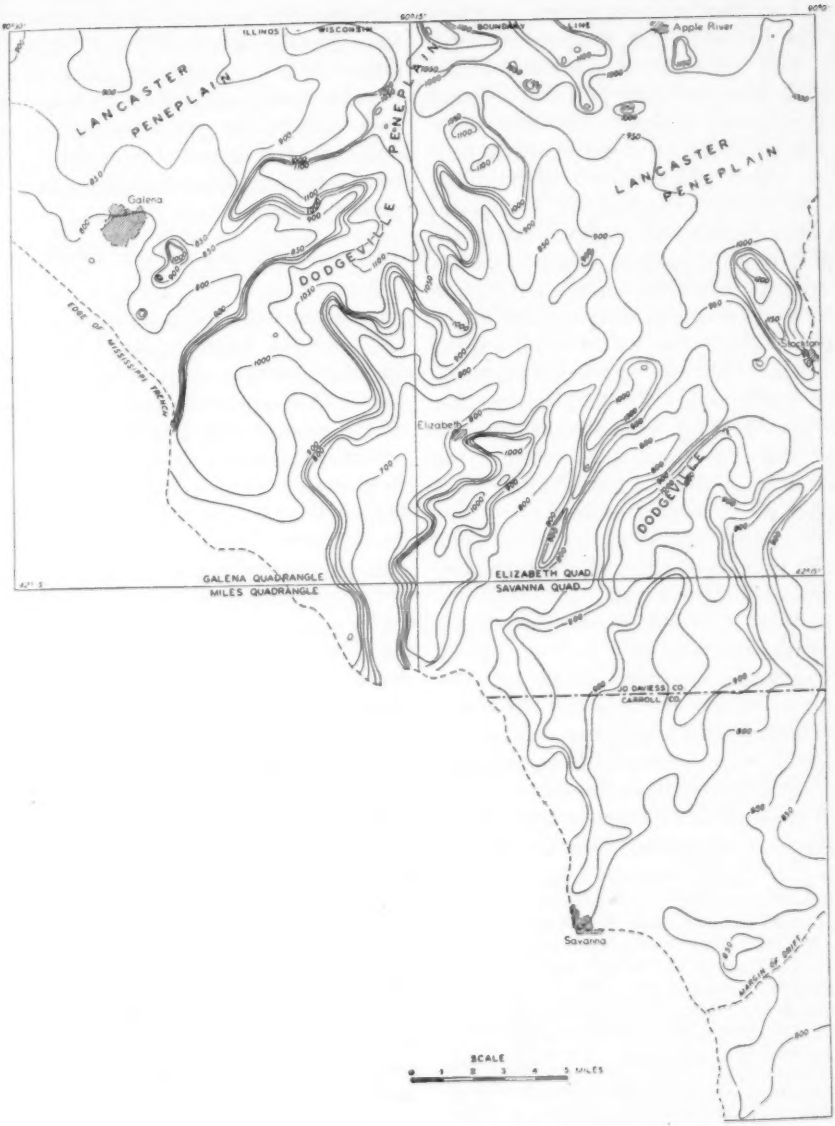

FIG. 4.—Generalized contour map of upland surfaces in the Driftless Area, northwestern Illinois

tion may be found in the higher structural position and diminished thickness of the Pennsylvanian strata to the west, so that resistant Mississippian limestones floor the lower portions of many large bedrock valleys. The local baselevels provided by these resistant beds may have been effective in retarding erosion of the uplands. This explanation, however, would not apply to the northern third of the upland, where Mississippian beds are absent, nor would it explain why erosion of the lower surface to the east was not also retarded by similar local baselevels along its western margin. For these reasons it is believed that structural control was not a major factor and that the escarpment between the two areas represents the junction of a higher and a lower peneplain.

Preglacial gravels of Lafayette type have been reported from Pike, Adams, Hancock, Fulton, Peoria, Tazewell, Warren, Henderson, and possibly Rock Island counties (Fig. 1).[28]

Correlation.—Summit areas in the southern part of the upland are continuous with the Calhoun peneplain of the driftless area of western Illinois described by Rubey[29] and those in the northern part are close to the required level. If the surface is projected northward across the Green River bedrock lowland, which separates the uplands of western Illinois from the Galena upland (Fig. 1), a correlation with the Lancaster peneplain is possible. Lower surfaces along the eastern and northern margins of the upland are probably extensions of the Central Illinois peneplain from the preglacial Pennsylvanian lowland to the east.

[28] A. H. Worthen, "Geology of Hancock County," *Geol. Surv. of Ill.*, Vol. I (1866), p. 330; "Geology of Pike County," *ibid.*, Vol. IV (1870), p. 37; "Geology of Fulton County," *ibid.*, p. 91; H. M. Bannister, "Geology of Tazewell, McLean, Logan, and Menard Counties," *Geol. Surv. of Ill.*, Vol. IV (1870), p. 179. Occurrences in Adams, Henderson, and possibly Rock Island county are reported by R. D. Salisbury in "A Further Note on the Ages of the Orange Sands," *Amer. Jour. Sci.*, Vol. XLII (3d ser., 1891), pp. 252–53, and in ftn. 14. The occurrence in Peoria County was noted by J. A. Udden in "The Geology and Mineral Resources of the Peoria Quadrangle," *U.S. Geol. Surv. Bull. 506* (1912), p. 50, and possible occurrences in southern Pike and eastern Warren counties were reported by J. E. Lamar (personal communication [1945]).

[29] Ftn. 13.

UPLAND SURFACE IN SOUTHWESTERN ILLINOIS

Description.—The bedrock upland northwest of the southern Illinois driftless area in Monroe, Randolph, and Jackson counties is covered by relatively thin drift and forms a prominent feature of the present topography (Fig. 1). A central ridge which rises to a maximum elevation of over 700 feet extends along the length of the upland and is bordered by extensive flattish summit areas. The summit areas have a general elevation of 600–700 feet north of Kaskaskia bedrock valley and 600–650 feet south of the valley. The upland is underlain by Mississippian (Osage, Meramec and Chester) strata and represents a segment of the Salem plateau of the Ozarks isolated by the Mississippi River.

Correlation.—The upland was considered a part of the Ozark topographic dome by R. F. Flint,[30] and on the basis of projected profiles was interpreted as an upwarped peneplain. It thus forms a northward continuation of the Ozark peneplain from the driftless area to the south. Northwestward, the surface appears to continue across the Mississippi River into the St. Louis area[31] and to merge with the Calhoun peneplain of western Illinois.

[30] Pp. 634–36 of ftn. 19.

[31] N. M. Fenneman, "Physiography of the St. Louis Area," *Ill. Geol. Surv. Bull 12* (1909), pp. 52, 57; "Geology and Mineral Resources of the St. Louis Quadrangle, Missouri-Illinois," *U.S. Geol. Surv. Bull. 438* (1911), pp. 43–44.

CENTRAL ILLINOIS PENEPLAIN

Description.—This modified surface is believed to extend over most of the Pennsylvanian lowland and to be widely developed on the Niagara cuesta of northeastern Illinois. It is thus considered the most extensive erosion surface within the state. The surface is unusually uniform in elevation; and, throughout the northern three-quarters of the area, upland elevations in most places lie between the 600- and the 650-foot contours; to the south they descend to about 500 feet (Fig. 1*)*. The highest sections of the upland rise about 100 feet above the general level in the east-central part of the state and form broad crests which conform closely to preglacial drainage divides (Figs. 1 and 5). Small remnants of the surface may be present in the Pennsylvanian upland to the west, as previously noted, and also southwest of the Galena upland in northwestern Illinois.

There is a general coincidence of the surface with the Illinois structural basin, but a general lack of adjustment to local structures. Transection of structure is especially apparent along the LaSalle uplift, which extends northwest-southeast across the northern half of the area (Fig. 2). In the LaSalle region, beds ranging in age from Pennsylvanian to Ordovician (Shakopee dolomite) are beveled by the surface. Further lack of adjustment to structure is indicated by the possible extension of the surface onto the hard rocks of the Niagara cuesta of northeastern Illinois.

Three possible occurrences of preglacial Lafayette-type gravel are known within the area (Fig. 1): (1) on the bedrock upland at Pana, in Christian County, where a thin bed of ferruginous conglomerate with angular and rounded chert pebbles was penetrated at the base of the drift in a diamond-drill boring;[32] (2) near Sullivan, about 30 miles northeast in central Moultrie County, where about 15 feet of ferruginous conglomerate with quartz and chert pebbles, mixed with weathered Pennsylvanian siltstone at the base of the drift, were identified by the writer from well sample cuttings; and (3) near Wedron, in LaSalle County, in the northern part of the area, where 2–4 feet of limonitic conglomerate and sandstone with polished chert pebbles directly overlies the bedrock.[33] The two latter deposits occur below the highest part of the upland at elevations of about 485 and 550 feet, respectively, and may be reworked from a former extensive upland gravel.

Correlation.—The surface is believed to represent a single peneplain developed largely on the weak rocks of the Illinois basin below the level of older erosion surfaces to the north, west, and south. The surface was recognized previously in various parts of southern Illinois[34] and in most cases was ascribed to a "third cycle" of erosion, completed in the Tertiary, following the two cycles represented by upland plains in the driftless areas of southern and northwestern Illinois.[35] In the northern part of the area

[32] Frank Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Surv. Mono. 38* (1899), p. 107.

[33] H. B. Willman and J. N. Payne, "Geology and Mineral Resources of the Marseilles, Ottawa, and Streator Quadrangles," *Ill. Geol. Surv. Bull. 66* (1942), pp. 204–5.

[34] E. W. Shaw and T. E. Savage, "Murphysboro-Herrin Folio, Illinois," *U.S. Geol. Surv. Atlas, Folio 185* (1912), p. 12, and "Tallula-Springfield Folio, Illinois," *U.S. Geol. Surv. Atlas, Folio 188* (1913), p. 10; E. W. Shaw, "New Athens-Okawville Folio, Illinois," *U.S. Geol. Surv. Atlas, Folio 213* (1921), p. 8, and "Carlyle-Centralia Folio, Illinois," *U.S. Geol. Surv. Atlas, Folio 216* (1923), p. 7; Wallace Lee, "Gillespie–Mt. Olive Folio, Illinois," *U.S. Geol. Surv. Atlas, Folio 220* (1926), p. 1.

[35] This is the conclusion of E. W. Shaw and T. E. Savage in ftn. 34 (1912), (1913); and Shaw (1921),

the surface has been clearly identified in LaSalle County and correlated with the Galena upland surface and the Dodgeville peneplain.[36] This correlation is not supported by the present study because of the physiographic discontinuity of the LaSalle County surface with the Galena upland plain and the possibility that the latter is continuous with the Lancaster peneplain rather than with the Dodgeville.

STRATHS ALONG MAJOR PREGLACIAL VALLEYS

A broad-valley stage preceding stream entrenchment is evidenced by possible straths along the preglacial Mahomet (Teays), ancient Mississippi, Kaskaskia, and Wabash drainage systems (Figs. 1 and 5). The existence of these surfaces is interpreted entirely from subsurface data, and they are related only indirectly to the alluvial plains which floor some of these valleys at present. The cyclical origin of some of the surfaces is uncertain because local baselevels and glacial changes may have been important factors in their development. Also, in some places the bedrock surface could not be delineated accurately because of insufficient data. It is significant, however, that the cumulative data indicate rock benches, which seem to descend regularly from 550 feet on the north to 450 feet and less toward the south, and that the valleys are much wider than those resulting from late preglacial entrenchment. Because of these features, an erosion level intermediate between the Central Illinois peneplain and the "deep-stage" valleys is postulated. It is named the "Havana strath" from the extensive bedrock lowland near the junction of the Mahomet (Teays) and ancient Mississippi bedrock valleys.

ENTRENCHED PREGLACIAL VALLEYS

The deep-stage valleys (Fig. 5) are entrenched 100 feet or more below the Havana straths and probably represent the final episode in preglacial erosional history. Although the preglacial age of the upper Mississippi bedrock valley may be open to question, there is evidence that Kansan and, possibly, Nebraskan drift is present in bedrock valleys of the ancient Mississippi, Rock, and Mahomet (Teays) systems, indicating that these valleys, and probably most of the deep bedrock valleys, were eroded to their present depths before the glacial period.

SUMMARY OF EROSIONAL HISTORY

The oldest erosion surface in the state may be represented by remnants of the Dodgeville peneplain in northwestern Illinois and the Buzzards Point plain in southern Illinois. Below these levels the Lancaster-Calhoun-Ozark peneplain appears to have developed as an extensive regional surface in late Tertiary time. Following completion of the peneplain, and probably prior to the making of the central Illinois peneplain, Lafayette-type gravels were spread over its surface,[37] and it appears likely that the positions of

(1923). Wallace Lee (pp. 1, 11 of ftn. 34) correlated the surface with the lower (Lancaster) surface in the Driftless Area and suggested its possible completion in the Mesozoic and uplift in the Tertiary.

[36] Willman and Payne, pp. 204–5 of ftn. 33.

[37] These gravels present numerous unsolved problems. Their age is indefinite "Tertiary" and it is probable that similar deposits of various ages are to be found in the upper Mississippi Valley as well as in the Gulf states. Similarities in composition could be explained by the re-working of an originally widespread deposit or by the repeated access to similar source materials. It is uncertain whether the gravels on the Lancaster-Calhoun-Ozark surface are older than the deposits at lower elevations in central and southern Illinois or whether they are essentially contemporaneous and therefore record important deformation of the peneplain.

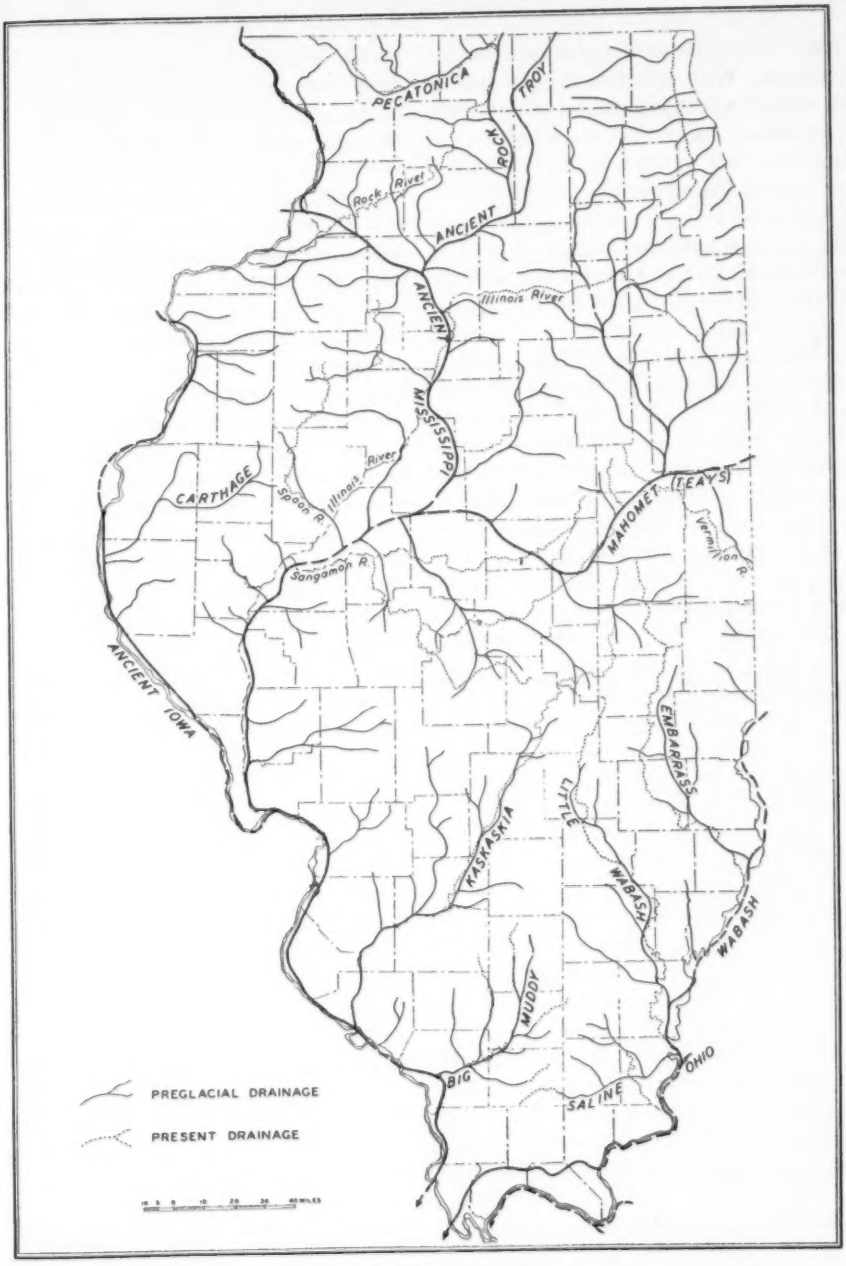

FIG. 5.—Major preglacial drainage systems in Illinois

major preglacial drainage lines were determined. With uplift of the peneplain, the larger streams in many places were established transverse to structure in superimposed valleys or in antecedent valleys on the upwarped peneplain surface. Outstanding transverse valleys in the state include the courses of (1) the ancient Mississippi across the west flank of the Wisconsin arch and Savanna-Sabula anticline in northwestern Illinois, (2) the ancient Rock across the positive element between the Sandwich fault zone and LaSalle anticline in north-central Illinois (Figs. 2 and 5), (3) the ancient Iowa and ancient Mississippi across the Cap au Grés structure in the Calhoun County area of western Illinois, and (4) the ancient Mississippi across the east flank of the Ozark dome in southwestern Illinois.[38]

During the third cycle of erosion which followed, a local peneplain was eroded on the weak beds of the Illinois basin. The extent of the surface to the east and northeast is not known, but to the north and west it is believed to terminate against remnant uplands of the older land surface. The ancestral Mississippi and Mahomet (Teays) were probably the major streams, although their courses may not have been established until the close of the cycle.

During the Havana cycle the main preglacial drainage lines were present and broad valleys were eroded along the ancient Mississippi, Mahomet, Kaskaskia, and Wabash systems. A rejuvenation of drainage initiated the deep-valley stage, which continued until interruption of the cycle by glaciation. This last cycle may have opened with the earth movements at the close of the Tertiary, in which event the main bedrock valleys could have been entrenched during the preglacial Pleistocene.

[38] Considered antecedent to the doming of the Ozark peneplain by R. F. Flint (ftn. 19).

NOTE ON THE GEOLOGY OF AGATTU, AN ALEUTIAN ISLAND

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ABSTRACT

Agattu is unique among the volcanic Aleutian Islands in being composed almost entirely of well-bedded sedimentary rocks. These rocks were clearly deposited in water and are composed chiefly of amorphous silica and fine detritus derived from a volcanic terrain. Igneous rocks are sparsely represented by intrusions of porphyry, diabase, and trap. The entire island has been heavily glaciated.

INTRODUCTION

Agattu lies 30 miles southeast of Attu, the most westerly island of the Aleutian chain, an arc of rugged volcanic islands stretching 1,000 miles across the North Pacific (Fig. 1). Agattu sprang into prominence early in the Aleutian campaign of World War II when Japanese ships anchored off its eastern shore. Actually, the Japs never occupied the island in force.

Agattu is 19 miles long by 10½ miles wide (Fig. 2). It consists of a rolling plateau a few hundred feet above sea-level, with a small range of mountains along the north shore.

The following observations were made incidental to 4 days' military duty on the island in July, 1945. They are of the roughest reconnaissance variety, as there was little time or opportunity for geological work. Only the area between Korab Cove and the east coast was covered on the ground. Supplementary information was obtained from Army Air Force aerial photographs. Lithologic descriptions are based solely on megascopic field examination.

BEDROCK GEOLOGY

GENERAL

Little has been published on the geology of the Aleutians, although they are known to be predominantly volcanic and to include a number of active volcanoes. Stratified deposits, some containing Tertiary plant and invertebrate remains, are reported to crop out sporadically in the Aleutians.[1] However, sedimentary rocks appear to be a minor constituent except on Agattu, 80–90 per cent of which consists of sedimentary beds.

SEDIMENTARY ROCKS

The sedimentary rocks of Agattu are chiefly fine grained, well bedded (Fig. 3), and rich in amorphous silica. Beds of pure chert are not common, but fully 25 per cent of the section consists of impure chert. In addition, most of the fine-grained strata are highly siliceous. Less abundant beds of particles in the medium- to coarse-sand size appear to have been derived from volcanic rocks of basic to intermediate composition. Massive layers of conglomerate containing subangular to subrounded fragments of volcanic rocks up to 3 inches in diameter constitute a small part of the section.

Various shades of gray and green predominate in the Agattu beds, supplemented by cream, brown, and purple. All the rocks are coherent, and the degree of cementation increases with decreasing grain size so that the finest rocks are hard and brittle.

Stratification is uniform and well de-

[1] S. R. Capps, "Notes on the Geology of the Alaska Peninsula and Aleutian Islands," *U.S. Geol. Surv. Bull. 857-D* (1934), pp. 143–44.

veloped, particularly in the fine materials where beds 1–3 inches thick predominate. The fine-grained rocks also show prominent lamination and are cut by a well-developed system of closely spaced fractures.

The Agattu beds are horizontal to gently inclined with dips up to 30 degrees. It seems likely that there are open folds, although none was observed. Strikes along the east coast are a little east of north and dips are east. Aerial photographs suggest a similar strike throughout much of the eastern half of the island. Linear fracture zones, probably faults, cut the sedimentary beds obliquely. Two of the most prominent fracture zones, trending N. 50° E. and N. 65° E., cross the island from Korab Cove to the east coast south of McDonald Cove (Fig. 4).

From exposures observed in sea cliffs, the thickness of these deposits need not exceed 400–500 feet. However, aerial

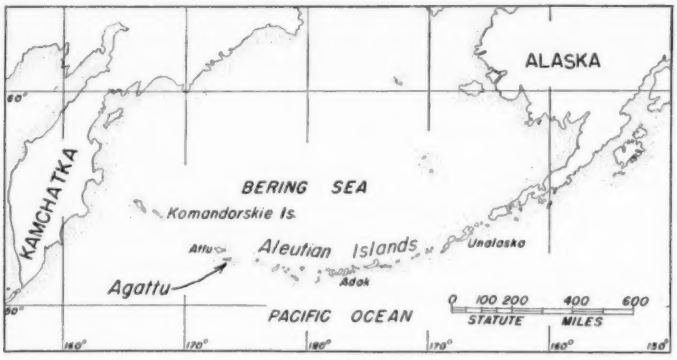

FIG. 1.—North Pacific Region

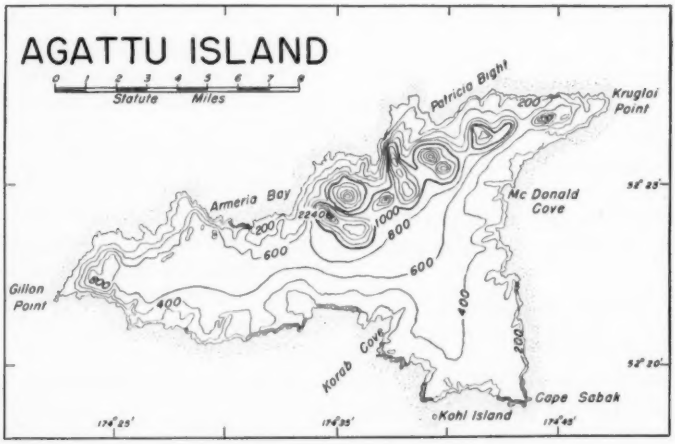

FIG. 2.—Agattu Island

FIG. 3.—Sedimentary beds, east coast of Agattu south of McDonald Cove

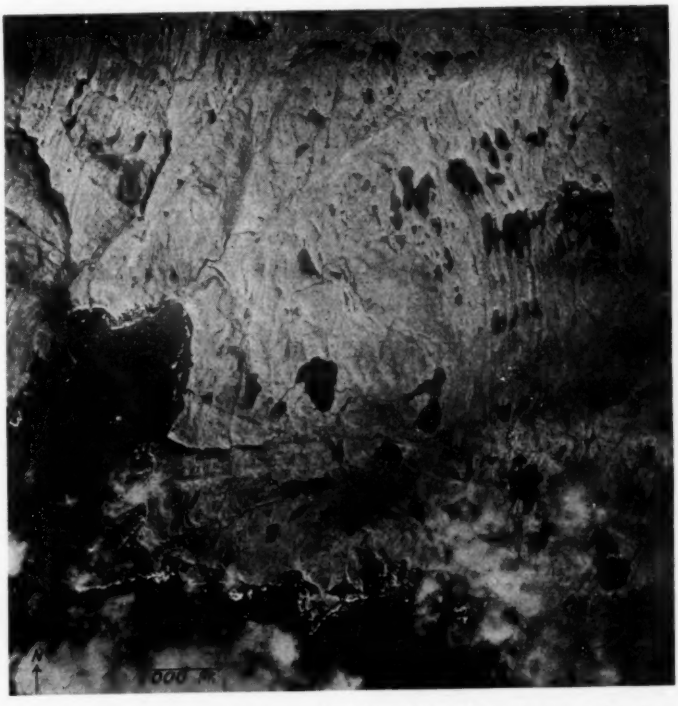

FIG. 4.—Vertical aerial photograph of Agattu Island in vicinity of Korab Cove, taken from 13,000 feet. (Official photograph, U.S. Army Air Forces.)

photographs show that the tops of peaks rising to 2,200 feet in the mountains of the north shore consist of nearly horizontal strata. If these mountains are composed wholly of beds in similar attitude, and it is so suggested by the photographs, the total thickness cannot be much less than 2,000 feet. Sections of inclined beds in the plateau require a similar minimum thickness unless duplicated by undetected faults or folds. It seems safe to state that the Agattu beds are at least 2,000 feet thick.

The bedding, sorting, and uniformity of these strata demonstrate deposition in water; whether fresh or salt is not known. Their composition shows that they were derived from a volcanic terrain, and the large amount of chert may suggest volcanic emanations in or near the basin of deposition.

The nature and origin of the basin in which the Agattu beds accumulated poses problems not solvable with the information available. If the Agattu beds are merely local, they may have been laid down in a great volcanic crater filled with either salt or fresh water. The Komandorskie Islands, 275 miles northwest of Agattu, and the Kamchatka Peninsula, 150 miles farther west (Fig. 1), contain sedimentary rocks.[2] The Komandorskies rest on a submarine ridge forming a northwestward continuation of the Aleutian ridge.[3] If the Agattu beds are related to the rocks exposed in the Komandorskies and Kamchatka, it is possible that sedimentary rocks may be an important constituent of the western Aleutian-Komandorskie ridge. In this case the basin of deposition would have been of considerable extent, and at least a partial diastropic origin of the western Aleutian-Komandorskie ridge is indicated rather than a simple *in situ* accumulation of volcanic rocks.

No fossils were found in the Agattu beds. They could be either Mesozoic or Tertiary. Their induration and lack of resemblance to any of the Tertiary strata on other Aleutian Islands[4] or the Alaska Peninsula[5] may indicate a pre-Tertiary age. They are certainly older than any of the igneous rocks seen on Agattu and resemble some parts of the thick Mesozoic section, particularly the Triassic, of the Alaska Peninsula,[6] although lithologic comparisons have little validity at such a great distance. Conversely the mild deformation of the Agattu beds, their content of volcanic debris, and the report of somewhat similar Tertiary strata on the Komandorskies[7] suggest a Tertiary age. Capps[8] did not see any

[2] G. M. Dawson, "Geological Notes on Some of the Coasts and Islands of Bering Sea and Vicinity," *Bull. Geol. Soc. Amer.*, Vol. V (1894), pp. 124–26, 129–30.

[3] H. W. Murray, "Profiles of the Aleutian Trench," *Bull. Geol. Soc. Amer.*, Vol. LVI (1945), Pl. I, p. 757.

[4] Capps, pp. 143–44 of ftn. 1 (1934); H. B. Collins, A. H. Clark, and E. H. Walker, "The Aleutian Islands," *Smithsonian Inst. War Background Studies No. 21* (1945), p. 6.

[5] W. H. Dall and G. D. Harris, "The Neocene of North America," *U.S. Geol. Surv. Bull. 84* (1892), pp. 242–57; W. W. Atwood, "Geology and Mineral Resources of Parts of the Alaska Peninsula," *U.S. Geol. Surv. Bull. 467* (1911), pp. 49–67; W. R. Smith and A. A. Baker, "The Cold Bay–Chignik District," *U.S. Geol. Surv. Bull. 755* (1924), p. 185; R. S. Knappen, "Geology and Mineral Resources of the Aniakchak District," *U.S. Geol. Surv. Bull. 797* (1929), pp. 195–98; Arthur Hollick, "The Tertiary Floras of Alaska," *U.S. Geol. Surv. Prof. Paper 182* (1936), p. 29.

[6] Atwood, pp. 30–48 of ftn. 5 (1911); P. S. Smith, "Areal Geology of Alaska," *U.S. Geol. Surv. Prof. Paper 192* (1939), pp. 37–38, 44–46, 50–52; S. R. Capps, "The Cold Bay District," *U.S. Geol. Surv. Bull. 739* (1922), pp. 92–105; W. R. Smith, "The Cold Bay–Katmai District," *U.S. Geol. Surv. Bull. 773* (1925), pp. 194–97; Smith and Baker, pp. 171–85 of ftn. 5 (1924).

[7] Dawson, pp. 124–25 of ftn. 2 (1894).

[8] Pp. 143–44 of ftn. 1 (1934).

rocks in the Aleutians that he considered pre-Tertiary, but he did not visit Agattu. Dall and Harris[9] favored a pre-Tertiary age for some Aleutian rocks but without any firm basis. However, the possibility that the Agattu beds may be older than Tertiary should be kept in mind, for a confirmation would indicate that the Aleutian ridge may be built in part of pre-volcanic rocks, as previously suggested.[10]

IGNEOUS ROCKS

In southern Agattu 3 miles east of Korab Cove a body of gray porphyry is exposed. Brief field observation suggests it is a small pluton intruded into the sedimentary beds. The rock contains large phenocrysts of feldspar, up to 1 inch long, and small crystals of hornblende and biotite set in a medium phaneric groundmass. From field examination the rock appears to be approximately a diorite.

On the south coast near Kohl Island is a massive intrusive of diabase rich in magnetite. Kohl Island is composed of the same rock. Aerial photographs suggest that Gillon Point at the western end of the island and Armeria Point on the north shore consist of diabase or similar rock. Diabase and trap dikes, 6 inches to 100 feet wide, cut the sedimentary beds. Most dikes are approximately vertical and strike within 25 degrees of east-west. A few have more northerly trends.

No extrusive rocks were observed on Agattu. The mountain peaks of the north shore have the external appearance of volcanoes but consist largely, if not entirely, of sedimentary beds.

[9] Pp. 244–45 of ftn. 5 (1892).

[10] Dall and Harris, p. 242 of ftn. 5 (1892); T. A. Jaggar, *Volcanoes Declare War* (Honolulu, T.H.: Paradise of the Pacific, Ltd., 1945), pp. 81–82.

GEOMORPHOLOGY

THE LANDSCAPE

Fully two-thirds of Agattu is a low rolling plateau, but along the north shore a small mountain range rises abruptly from the sea. The highest elevation known in these mountains is 2,240 feet. They are highest and most rugged from Krugloi Point to Armeria Bay. Peaks and ridges above 1,000 feet are sharp and angular; below 1,000 feet they are rounded and smoothed. Valleys are wide and U-shaped, and passes crossing the mountains are mostly low, broad, and open. Westward from Armeria Bay hills rise abruptly 700–800 feet from the sea on the north and drop off gently to the plateau on the south. Near Gillon Point these hills give way to a south-sloping plateau at 800–900 feet.

The remainder of Agattu consists of a rolling lake-dotted plateau at 300–500 feet with a relief usually less than 100 feet. Much of this plateau country has a distinct grain trending 10°–30° east of north (Fig. 4). In the eastern half of the island this grain is caused by tilted sedimentary beds, and the ridges are crests of low cuestas. In the western half the grain may be controlled by a well-developed joint system. Ridges held up by dikes and linear depressions along fracture zones cross the grain obliquely. Prominent depressions have been eroded along two major fracture zones extending east of north from Korab Cove. Since the plateau truncates the upturned edges of sedimentary beds, it is clearly an erosion surface, but whether of marine or terrestrial origin is not known.

Lakes are the most prominent feature of the plateau, and Agattu is estimated to have at least 1,000 ponds and lakes (Fig. 4). These water bodies are shallow and mostly less than ½ mile long. They

lie in rock basins, the shape and distribution of which are clearly determined by rock structure in many places (Fig. 4). Lakes lie at all elevations; some occupy basins on the sides and summits of ridges, and others are on valley floors. A number have no surface outlet, but approximately 75 per cent are drained by small streams running from one lake to another and eventually to the sea. Lakes are less abundant in the mountains, but here, too, they occupy rock basins and are scattered more or less haphazardly over the landscape up to about 1,000 feet.

Streams on Agattu are small and flow across the plateau in shallow irregularly winding valleys. Near the sea they plunge into deep, narrow, V-shaped gorges containing cascades and waterfalls. The largest stream on the island flows from some lakes north of Korab Cove eastward 4 miles to McDonald Cove.

The plateau is thinly mantled with soil and angular rock fragments on which grows a tundra mat of moss, grass, and low heath.

Practically the entire shore of the island is bordered by vertical sea cliffs 50–200 feet high. Stacks, arches, and offshore reefs are abundant. The few bouldery, narrow beaches are limited largely to the heads of coves and bays.

GLACIATION

Cirques and U-shaped valleys in the mountains, rounded and grooved bedrock outcrops on the plateau, and the abundant rock-basin lakes all suggest extensive glaciation; but moraines, other deposits of drift, and striated bedrock surfaces have not been seen. However, by comparison with the islands of Attu and Adak, where evidence of glaciation is irrefutable, there can be little doubt that Agattu has been heavily and extensively glaciated.

Ice covered the entire island with the possible exception of the highest peaks and ridges. All areas below 1,000 feet show smoothing, scouring, and excavation. The lack of drift can be attributed to the fact that the ice flowed into the sea on all sides.

The north-shore mountains were presumably the initial gathering area for snow, and the ice streams so nourished flowed down onto the plateau to the south, where they coalesced to form a piedmont glacier. That the plateau ever had a true ice cap with a center of nourishment independent of the mountains is possible but not certain. Judging from the elevation of cirque floors, the size of the ice mass, and evidence of glaciation on near-by low-lying islands, the glacial snowline on Agattu must have been no higher than 800–1,000 feet. The present snowline lies above the highest peak, 2,240 feet, and may be about 3,300 feet in the eastern Aleutians.[11] The ice covering the plateau must have been at least 200–300 feet thick in order to move, scour the bedrock, and excavate the lake basins. Parts of the upper surface of this plateau ice could easily have approached 800 feet and may have been high enough to receive nourishment independently of the mountains. In this way it could have become an independent ice cap.

The raw freshness of the topography, lakes, and rock surfaces indicates the relative recency of the glaciation. However, erosion of sea cliffs and postglacial stream gorges suggests that ice has not covered the entire island since the post-Wisconsin optimum,[12] which started ap-

[11] J. Wascowicz, "Studies on the Snow-Line in Canada and Alaska," *Acad. Polonaise Sci. and Letters, Intern. Bull. Series A* (1929), Fig. 4, p. 395.

[12] The period of warmest and driest climate following the Wisconsin has been called the middle post-Pleistocene optimum, the postglacial optimum, the postglacial climatic optimum, and simply the climatic optimum. R. F. Flint ("Progress and Prob-

proximately 7,500 years ago.[13] Ice almost completely covered Agattu during the late Wisconsin and may have remained on parts of the island well into the post-Wisconsin period. The fact that there are no glaciers on the island today indicates that the ice was completely gone by the culmination of the post-Wisconsin optimum, a warmer, drier period than the present. Unfortunately, field observations were not complete enough to throw any light on the possibility of a rebirth of glaciers following the post-Wisconsin optimum. Present-day glaciers in the Aleutians all lie at much higher altitudes than the highest parts of Agattu.

SOIL STRUCTURES

Turf-banked terraces[14] are well developed and widely distributed. They show prominently on aerial photographs taken from 13,000 feet. The terraces are 2–15 feet wide, 20–100 feet long, and have an outer face 2–3 feet high. The treads are covered with a mixture of loose soil and rock fragments, and the outer faces are banked with turf consisting of soil, grass, moss, and scrubby heath.

Small stone nets and stripes were seen on bare flats and gentle slopes mantled with loose soil and rock fragments. The nets are usually 12–18 inches in diameter and the stripes of corresponding width. Their fresh appearance and the lack of stabilizing vegetation suggest that they are currently active.

CONCLUSIONS

At least 2,000 feet of well-bedded sedimentary rocks are exposed on Agattu. They are composed largely of amorphous silica and fine detritus derived from a volcanic terrain. The strata are gently tilted, faulted, and possibly folded. Approximately 80–90 per cent of the island consists of sedimentary rocks. Small intrusive bodies of porphyry, diabase, and trap compose the remaining 10–20 per cent.

The existence of this considerable body of sedimentary rocks in the otherwise predominantly volcanic Aleutian chain raises questions concerning the constitution and origin of the western Aleutian-Komandorskie ridge. If the Agattu beds are local, they need be of little significance; but if they are related to sedimentary rocks in the Komandorskie Islands and the Kamchatka Peninsula, a significant part of the western Aleutian-Komandorskie ridge may consist of similar materials. This would indicate an extensive basin of deposition and at least a partial diastrophic origin for the ridge.

No fossils were found in the Agattu beds; they could be Mesozoic or Tertiary. If Mesozoic, the possibility that the entire Aleutian ridge is composed in part of Mesozoic strata should be considered.

Like many other Aleutian Islands, Agattu has been almost completely covered by ice, and the marks of glaciation are fresh and widespread. Ice probably occupied at least parts of the island until the post-Wisconsin optimum. It did not survive the optimum, and there are no glaciers on the island at present. Glacial snowline was 800–1,000 feet above sea-level.

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lems in the North American Pleistocene," *Jour. Geol.*, Vol. L [1942], pp. 570–71) has restated the disadvantages of the term "postglacial" and proposes that Pleistocene be substituted for "Quaternary." Therefore, it is suggested that the warm period following the Wisconsin simply be called the post-Wisconsin optimum.

[13] Ernst Antevs, "Postpluvial Climatic Variations in the Southwest," *Bull. Amer. Meteorological Soc.*, Vol. XIX (1938), p. 190.

[14] R. P. Sharp, "Soil Structures in the St. Elias Range, Yukon Territory," *Jour. Geomorph.*, Vol. IV (1942), p. 275.

SAND GRAINS AND PERIGLACIAL CLIMATE: A DISCUSSION

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ABSTRACT

The present paper discusses the work of André Cailleux on Quaternary periglacial wind action in Europe, published during the war as a memoir of the Société géologique de France. Cailleux has outlined the periglacial zone chiefly on the basis of the distribution of wind-worn sand grains in Quaternary deposits. It is felt that this new criterion, although overextended by Cailleux, is basically sound and is additional proof for a cold, windy climate adjacent to the ice sheets—a climate demonstrated by such well-known indicators as loess and frost-produced soils.

Students of the Pleistocene are familiar with the loess belt of Europe, which extends from northern France eastward to Poland and the Ukraine. According to current European opinion, as summarized by F. E. Zeuner,[1] this belt during the glacial stages of the Pleistocene was a grass steppe characterized by cold summers and colder winters. It was separated from the ice sheet by a barren tundra zone. The cold winds induced by the ice sheet picked up the fine-grained material supplied by glaciofluvial deposition and by frost-weathering in the tundra zone and deposited it as loess on the grass steppe.

Additional evidence for strong winds adjacent to the ice sheet is the presence of wind-cut pebbles (ventifacts) in glacial deposits. Evidence for low temperatures in the periglacial zone has long been available in the abundant examples of fossil soils produced by intensive frost action. The meteorological reasons for such a cold, windy climate are outlined by C. E. P. Brooks.[2]

But what of the material intermediate in size between pebbles and loess? Does the sand show evidence of periglacial wind action, either in abrasion (like ventifacts) or in deposition (like loess)? A recent paper by André Cailleux[3] has revealed the evidence. Although deposits of wind-blown sand are not widespread in the periglacial area, Cailleux believes that the individual sand grains, whether finally deposited by water, ice, or wind, show the mark of wind abrasion during the Pleistocene.

In this study, extending over a period of ten years, Cailleux separated out a coarse sand fraction (0.4–1.0 mm.) from about three thousand samples of European Quaternary deposits. He distinguished four types of quartz sand grain: (1) angular and unworn; (2) subangular to rounded, with a shiny surface; (3) rounded with a frosted (mat, groundglass) surface; and (4) rounded with a frosted surface but retaining traces of cement or recrystallization formed in a pre-Quaternary cycle of deposition, and thus to be eliminated in the study of Quaternary conditions of abrasion.

Types 2 and 3 are differentiated more by the surface features than by the degree of rounding. The frosted surface consists of many tiny pits and crescentic percussion marks, which disperse the light evenly and give the whole surface a

[1] "The Climate Adjoining the Ice-Sheet of the Pleistocene," *Proc. Geol. Assoc. London*, Vol. XLVIII (1937), pp. 379–95.

[2] *Climate through the Ages* (London, 1926). Pp. 439.

[3] "Les Actions éoliennes périglaciaires en Europe," *Mém. Soc. géol. France*, No. 46 (1942). Pp. 166.

rough, dull aspect, no matter which way the grain is held. The shiny surface is smooth and polished; the translucence of the grain depends upon the position in which the grain is held.

Cailleux believes that the rounded, frosted grains were produced by wind abrasion and the shiny grains by water abrasion. This theory is not new. The extended controversy concerning the relative effectiveness of wind and water in rounding sand grains has recently been summarized by W. H. Twenhofel.[4] Field observations and experiments seem to be pointing to wind as the more effective rounding-agent, bearing out the theoretical approach that wind-borne sand grains have a higher velocity, higher apparent density, more direct impacts with other grains, and, thus, greater abrasive power. The additional factors of selective transportation and of complex histories must be eliminated before generalizations are justified.

The frosted surface, most workers agree, is also best produced by abrasion in wind. It is not definitely known, however, at just what stage in the rounding the frosted surface appears. The present writer has observed subrounded and even subangular grains which have patches of frosting, usually on the more rounded portions of the grains. He has also seen well-rounded grains which are completely frosted except for places where small conchoidal chips have been broken off. Presumably, then, frosting can be formed during any stage in rounding, but in the early and middle stages it does not persist because the rate of removal of small chips is too great. In advanced stages of rounding, such chips are knocked off less frequently and frosting can be retained over the entire surface.

It is not known under what conditions the frosting can be removed. Cailleux[5] states that he was able to remove a frosted surface and develop a shiny surface on grains of calcite by aqueous abrasion representing 50 km. of travel. Rounded, shiny grains are commony associated with rounded, frosted grains.[6] Were the former produced directly from unworn grains by abrasion in water, or were they produced from frosted eolian grains during a later cycle of aqueous abrasion? Experimental work should eventually establish the answer to this problem.

Cailleux believes that the percentage of frosted grains in the coarse sand fraction studied by him is a measure of the intensity of wind action for the approximate time and place of deposition. His map of the distribution of Pleistocene frosted sand grains (Fig. 1) shows that the larger percentages (40–100) are found in a broad belt extending from northwestern Germany to Poland. As the Tertiary deposits of these areas normally contain less than 5 per cent frosted grains, the contrast is striking. This belt of frosted sand grains lies, in general, between the loess belt and the Pomeranian moraines of the last glacial stage. It is strongest in central Poland, where 80–100 per cent of the coarse sand grains are frosted. Cailleux believes that the stronger wind action thus indicated in the east is a result of greater continentality of climate. Zeuner[7] had arrived

[4] "Rounding of Sand Grains," *Jour. Sed. Pet.*, Vol. XV (1945), pp. 59–71.

[5] P. 36 of ftn. 3.

[6] H. C. Stetson, "The Sediments of the Continental Shelf off the Eastern Coast of the United States," *Papers in Physical Oceanography and Meteorology, Mass. Inst. Tech. and Woods Hole Oceonographic Inst.*, Vol. V (1938), No. 4.

[7] Ftn. 1.

at the same conclusion from the study of the loess belt, which is wider to the east. Zeuner also pointed out that the climate in the west must have been correspondingly more oceanic because of the more common occurrence in the west of (frosted) sand grains and the terminal positions of the ice sheets. However, in the case of any of the older glacial stages, there probably would not be a sufficient number of samples to justify contours with intervals as small as 20 per cent.

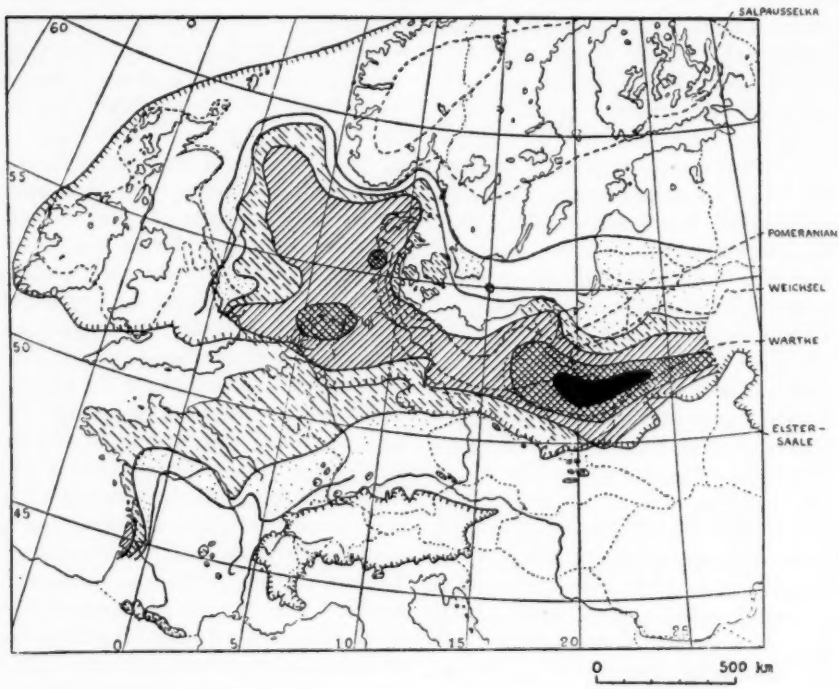

FIG. 1.—Distribution of frosted (wind-worn) sand grains in Quaternary deposits of northern and western Europe. Black pattern, more than 80 per cent of the coarse (0.4–1.0 mm.) sand grains are frosted; cross-hatched, 60–80 per cent; diagonal lines, 40–60 per cent; dashed diagonal lines, 20–40 per cent; dots, 10–20 per cent; white, less than 10 per cent. The northern margin of the loess belt coincides roughly with the barbed line which represents the Elster-Saale or maximum extension of the Quaternary ice sheets. Moraines of the last glaciation are shown by dashed lines and labels. (After Cailleux, Fig. 16 of ftn. 3.)

solifluction soils, which require a cold, moist climate.

This distribution map of frosted sand grains includes deposits of all glacial and interglacial stages of the Pleistocene. A separate map for each glacial stage would reveal more accurately the relations between concentrations of eolian Presumably, most of Cailleux's samples came from the widespread deposits of the last glacial stage, so his published composite map (Fig. 1) must show most accurately the relations for this stage. At best, the contours indicate only the general distribution of eolian grains.

The map shows that the belt of high

concentration of eolian grains lies north of the Elster and the Saale terminal moraines, in part north of the Warthe (last glaciation, phase 1) and the Brandenburg or Weichsel (last glaciation, phase 2) moraines, and entirely south of the Pomeranian or Great Baltic (last glaciation, phase 3) moraines. Therefore, most of the sand grains must have been rounded and frosted before the pre-Pomeranian ice sheets reached their terminal positions, or during the early stages of their retreats. All the ice sheets must have expanded fairly rapidly until they reached the southern coast of the Baltic Sea. The subsequent advance and retreat to and from the terminal position must have been slower and the pause at the terminal position brief. In this way a maximum amount of time would be available for wind abrasion in the areas now marked by high percentages of eolian grains.

Cailleux makes much of the low percentage of eolian grains in the deposits of the retreat from the Pomeranian moraine. He states that the decrease was caused by a rapid improvement of climate, which was not registered by an equally rapid retreat of the huge, inert ice sheet. The barren tundra zone marginal to the ice sheet was replaced by advancing forests, the winds decreased, and fewer sand grains were frosted. He even suggests that the Scandinavian ice sheet might have "waited out" the last (Riss-Würm) interglacial, which was so well represented in the smaller, more sensitive Alpine ice sheet. Such a suggestion ignores the well-established correlation of the late Scandinavian and Alpine glacial and interglacial stages. The low percentages of eolian grains in late-glacial deposits may be explained much more simply by noting that such deposits are confined to areas which were covered by ice during most of each glacial stage. The sand grains in these areas thus were not available for abrasion in the periglacial winds. Furthermore, if there was such an abrupt decrease in the number of eolian grains produced in late-glacial time, one would expect even greater decrease in interglacial deposits. The great Elster-Saale interglacial stage lasted much longer than late-glacial time and had a more temperate climate. Yet, according to Cailleux, deposits of the interglacial stages show high percentages of eolian grains (Table 1).

TABLE 1*

SECTION OF SURFICIAL DEPOSITS NEAR WARSAW

	Per Cent Coarse Sand Grains Frosted
Moraine (last glaciation)	70
Sand (last interglacial)	80
Moraine (older glaciation)	65–70
Preglacial (early Pleistocene) derived from the north	70–80
Preglacial (early Pleistocene) derived from the Carpathian Mountains	5–80
Pliocene	5

*Extracted from table on p.81 of ftn. 3.

There is little evidence for strong wind action in these areas during interglacial stages; so the frosted sand grains in interglacial deposits must have been derived from the deposits of the preceding glacial stages. It is surprising that fresh or shiny sand grains were not supplied by interglacial chemical weathering and stream abrasion in sufficient quantities to reduce the concentration of frosted grains.

Cailleux overlooks these relationships. He does not state the number of interglacial deposits sampled, the conditions of deposition, or the source of the sediment. Perhaps such details of description could not be presented because of the

large scope and reconnaissance nature of the study. In many cases the information probably was not available because the sampled deposits were inadequately studied. In other cases the samples were not collected by Cailleux himself but were sent to him by other individuals.

The accuracy of the distribution map (Fig. 1) and the correctness of the interpretations depend partly on the methods of sampling, particularly when the samples are supposed to represent all of Europe during all of the Quaternary. Half of the samples came from fluvial and lacustrine deposits; the remainder from moraines, frost-produced soils, and eolian deposits. Apparently, the sand grains were scattered over the entire barren tundra zone after having been rounded and frosted by abrasion in the wind. Final transportation and deposition by the advancing ice or by glaciofluvial streams did not change appreciably their wind-worn character or add many fresh, unworn grains. However, Cailleux does not state what percentage of the whole sample is represented by the frosted grains. A sample of boulder clay with 1 per cent coarse sand (0.4–1.0 mm.) has a different statistical value from a sample of well-sorted eolian or fluvial sand with 80 per cent coarse sand, even though 65 per cent of the coarse sand grains in each case may be rounded and frosted.

In addition to eolian sand grains, Cailleux studied the distribution of ventifacts and frost-produced soils in Quaternary deposits. He found that, in general, more ventifacts and more intense frost action have been reported from areas which have high percentages of eolian sand grains. He measured the relative intensity of frost action by noting the number of ventifacts larger than 10 cm. which were wind-worn on all sides. This novel method is based on the belief that pebbles of this size, after being worn on the face or faces exposed to the wind, were too large to be blown over by the wind and, therefore, must have been turned over by some other agent. Action of animals or undermining by wind or rainwash on sloping ground are considered to be unimportant. The fact that ventifacts are so often associated with frost-produced soils indicates that frost action was available to overturn these stones. Furthermore, this scale of intensity of frost action fits well into our general picture of the periglacial climate.

Cailleux found numerous overturned ventifacts and frost-produced soils (even ice wedges) in central and western France as far south as Bordeaux, and around the Alps. With the exception of the great ancient coastal dunes of Les Landes, there are low percentages of rounded and frosted sand grains in the Pleistocene deposits of these areas. The conditions of sand supply, sand disposal, and vegetation may have been such that no one grain could undergo enough wear to acquire a rounded and frosted character. In Iceland, for instance, ventifacts are being formed today in great abundance, but the sand grains are angular. This is the more remarkable because these grains are fragments and minerals of volcanic rock, which is less resistant to abrasion than is quartz, the dominant mineral of European periglacial areas.

In conclusion, it may be stated that Cailleux's eolian sand grains provide one more criterion useful in determining the nature of the Pleistocene periglacial climate in Europe. Some of his detailed correlations are hardly tenable, largely because his methods of sampling are either inadequate or insufficiently explained. However, his main theses may be ac-

cepted: (1) Pleistocene deposits of the periglacial area contain more eolian sand grains than Tertiary deposits of the same areas; (2) the higher percentages (40–100) of eolian sand grains are found in a belt between the loess belt and extended positions of the ice sheets; and (3) this belt is strongest to the east, where the climate was more continental. His study of the distribution of ventifacts and frost-produced soils provides confirmatory evidence. These three main conclusions fit well into our general conception of the periglacial climate as determined from other criteria, such as loess, tundra soil, and cold-type flora and fauna.

ACKNOWLEDGMENT.—The writer is greatly indebted to Kirk Bryan for criticism of this discussion.

REVIEWS

Vertebrate Paleontology. By ALFRED S. ROMER. 2d ed. $7.50. Chicago: University of Chicago Press, 1945. Pp. 687; figs. 377; tables 4.

Paleontologists and students in related fields will welcome the appearance of the second edition of Romer's *Vertebrate Paleontology* at a time which has witnessed diversion of many of their numbers to other fields of activities and sharp reduction in the interchange of information between countries. Since 1933, the date of publication of the first edition, great strides have been made in the studies of vertebrate evolution. The second edition of *Vertebrate Paleontology* takes note of the important developments and incorporates them into the story of vertebrate history. About one-half of the text has been re-written; important changes in classification have been introduced; new figures have been added; some old ones have been replaced; and important additions to the contents have been incorporated.

Certain modifications may be cited as being of particular importance. The section on the fishes has been materially increased to include a moderately extensive account of the teleosts, a group treated with disproportionate brevity in the first edition. A new classification of the amphibians has been proposed. This is an area in which Romer has been particularly active, so that his concepts take into consideration the best thought on the group and offer an intelligent co-ordination of the present status of knowledge. Two major subdivisions of the class are recognized: the subclass Apsidospondyli, which includes the superorders Labyrinthodontia and Salientia; and the subclass Lepospondyli, including not only the typical "Coal Measures" orders but the Urodela and Apoda as well. The subclass Seymouriamorpha is removed from the class Reptilia and included as an order of the superorder Labyrinthodontia. *Amphibamus* and *Miobatrachus* of the North American Pennsylvanian are recognized as ancestral Anura, following Watson, and constitute the known members of the order Eoanura.

The treatment of the reptiles has not been materially altered except for occasional modifications which take cognizance of developments of the last decade. The tritylodonts, classed as mammals in the earlier edition, are placed with the ictidosaurs, among the reptiles. The chapter on birds is little changed. The pattern of the section dealing with mammals is much the same as in the first edition except that consideration of the Primates, which constituted the last chapter in the first edition, is shifted to follow the material on primitive placental mammals. The classification, however, has been brought up to date, and the text has been altered in accord with the changes.

A notable addition to the book is three new chapters devoted to vertebrate history. In the earlier edition the reader was obliged to reconstruct this history from brief remarks in the systematic treatment, and little concerning the nature and distribution of deposits was available. This section begins with a very brief series of statements concerning correlation, the nature of evidence, effects of environmental differences on faunas, climates, and migrations. Although these furnish a basis for thought on these important matters, the treatment is so brief that many students will fail to understand the full significance of these matters. This introduction is followed by an analysis of the faunas of each period, from the Cambrian to the present. Three tables list some of the most important vertebrate-producing localities, giving their position in the appropriate continent and their approximate geological age. This section, although brief, performs an important function in making the book of greater value to the nonspecialist, particularly to paleontologically minded geologists. It also serves as an excellent summary for students who may become lost in the extensive detail of the systematic and morphologic sections.

The classification of the vertebrates, synoptic in the first edition, has been greatly expanded—from 17 pages to 54 pages. The expansion results primarily from the listing of the majority of important fossil genera and an increased number of extant types. As before, the family reference, the geological age, and the continent or continents in which genera occur are noted. The classification is comprehensive

but, of course, far from complete. The Bibliography is expanded to include recent publications as well as a more extensive series of older works. As in the first edition, comments follow many of the references. These aid the student materially in his effort to select reading materials on a particular group. The Index is enlarged, in keeping with the expansion of the classification. It is primarily taxonomic; but many morphological, geological, and geographic terms are included.

This book, as was true of its predecessor, is indispensable as a reference work in the teaching of vertebrate paleontology. It may be used as a text for a comprehensive course on phylogeny, taxonomy, general morphology, and stratigraphic and geographic distribution of the vertebrates. A student lacking background in basic vertebrate anatomy and phylogeny may, however, find himself lost in some sections of the text, as a result of the array of facts which he must master. This proved to be the case in the first edition and cannot, perhaps, be avoided in a text which follows a systematic scheme of organization and is at all comprehensive. The use of illustrative specimens with the text aids materially in reducing this difficulty. It is doubtful that a student working independently with the text without extensive collections can gain an adequate concept of the field unless he already has a strong background in related fields. The presentation of phylogeny, morphology, and general stratigraphic position and range of groups simultaneously must necessarily be difficult to follow. The segregation and amplification of stratigraphic work in the new edition goes part way in remedying this difficulty.

The format of the text has been improved by the substitution of heavy, large type for italics in the subheadings of the chapters. The illustrations are mostly by L. I. Price and in most instances are based on published figures. They are line drawings with stipple shading. It is unfortunate that a book of such importance had to be printed on the relatively inferior paper demanded by wartime restrictions. Some of the illustrations have suffered considerable loss of detail thereby.

The value of the text as a reference book has been materially increased, especially by expansion of the classification. Its value to students has been augmented by bringing recent advances into a general picture. But the increase in coverage, while certainly of value to advanced students, will make an already difficult subject even more forbidding to an elementary student. The book is of more value to the specialist in one area of vertebrate paleontology who desires some knowledge of related areas. The stratigraphic section should prove of particular value to geologists and to students of the biological sciences who wish to develop a perspective of time in evolution as an aid to their work with modern animals.

EVERETT C. OLSON

"Macquarie Island: Its Geography and Geology." By DOUGLAS MAWSON. *Australian Antarctic Expedition, 1911–1914.* ("Scientific Reports," Ser. A, Vol. V.) Sydney: Government Printer, 1943. Pp. 194; figs. 46; pls. 37; 2 maps in color. £1 15*s*.

Sir Douglas Mawson has prepared this report mainly on the basis of the survey, notes, photographs, and collections made by Leslie R. Blake during a two-year sojourn on the island. Shortly after Blake's return to Australia in 1914, he volunteered for war service; he was killed in France on almost the last day of hostilities. Mawson has added his own observations during two short visits to the island.

Macquarie lies nearly halfway between New Zealand and Antarctica, as the emerged portion of a submarine ridge that has now been traced for a length of 250 miles and apparently extends a New Zealand tectonic line. The island may be described as a mountain range, planated prior to the glacial epoch but now rising abruptly from the sea in cliffs. Faulting has been important recently and still causes frequent earthquakes.

The oldest formation recognized is Blake's Older Basic group, a thick series of basaltic flows and sills with associated tuffaceous graywacke, possibly of Tertiary age but more probably dating back to Middle Mesozoic time, and perhaps referable to the period of large-scale intrusions of dolerite into the Triassic sediments of Tasmania and Antarctica. These old rocks were intensely folded (Cretaceous? or early Tertiary?), while into the folded system were injected gabbroic magmas, which, by gravitative differentiation, have yielded a well-graded series of gabbros and peridotites. Both the grain of the folding and the long axes of the intruded masses trend northwest-southeast (pointing, it might be noted, toward Tasmania).

The axis of the present long, narrow island, however, is N. 14° E.

Erosion laid bare the plutonic masses. Later subsidence was sufficient for a deposit of globigerina ooze to be spread over the beveled structures. Magmas of the younger Basaltic group broke through this, but globigerina ooze continued to form amid the basaltic pillow lavas and breccias. Their age may be Miocene. The volcanic period ended with a land area probably larger than the present island. Pleistocene glaciation was severe.

The igneous rocks have been well studied petrographically, with accompanying tables of chemical analyses, and many of the individual specimens are described in detail. The photographic plates at the end of the report are excellent.

R. T. C.

Physiographic Diagram of Asia. By A. K. Lobeck. Small scale ed. New York: Geographical Press, Columbia University, 1945. Scale, 1:20,000,000. Separate text, pp. 8. Map sheet (24 × 38 in.). Without the text $0.35 (10 or more, $0.25 each). Map and text, $0.70 (10 or more, $0.50 each).

Professor Lobeck's well-known series of physiographic diagrams has now been extended to include Asia. This newly issued diagram, including Europe and the Dutch East Indies in opposite corners without appreciable reduction in the size of Asia, measures 22 × 24 inches. It is a clear-cut picture of Asia's facial features. On the reverse side of the sheet is a corresponding map of the physiographic provinces with the major groups, smaller units, and lesser subdivisions named and systematically numbered (or lettered) in accordance with Lobeck's classification. Owing to the large number of physiographic units recognized (no fewer than 255 smaller subdivisions), this black-and-white map is most valuable for its details. The recommended coloring, however, will doubtless make the larger relations stand out more distinctly.

Alongside the diagram is a double-column discussion in fine print of the size, location, climate, vegetation, people, history, culture, and religion of Asia. In spite of the diversity of topics handled in this limited space, the general understanding obtained by the reader is distinctly good, and the reading is by no means dull. On the map side of the sheet, a complete tabular classification of the physiographic divisions fills an entire column. An adjoining column gives instructions for tinting the diagram and coloring the map, together with much other pertinent information. The map scale of this small-size edition makes the sheet very convenient for desk use, thus obviating bothersome trips to consult wall maps and their like. Folded to about the size of a quarto page, the map sheet can be filed together with the text sheet in an ordinary desk drawer.

The text sheet is of the same size as the map sheet and is so printed on both sides that, by folding, its eight pages become arranged in proper sequence. Here is given judicially selected information on all the physiographic divisions, large and small, arranged in the order of the classification table on the map sheet. A surprising amount of useful factual material has been packed in very small space.

R. T. C.